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CURRENT SYSTEMS IN THE VESTIGIAL GEOMAGNETIC FIELD: EXPLORER VI*†

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The purpose of this Letter is to present some preliminary data taken by the magnetometer carried by the satellite Explorer VI. These data indicate the existence of a temporally and spatially variable current system which strongly perturbs the geomagnetic field at geocentric distances of 5 to 7 R_e (earth radii).

The Explorer VI orbit is extremely eccentric with an apogee of 48 800 km and a perigee of 6700 km geocentric. The period of rotation is approximately $12\frac{3}{4}$ hours. The plane of the orbit is inclined 47° with respect to the geographic equator. In terms of the orbital orientation with respect to the sun, apogee occurs between local dusk and midnight, i.e., 2100 hours local time, with perigee occurring at 0900 local time.

The magnetometer used was a search coil mounted on the inner shell of the spin-stabilized vehicle, as in Pioneer I.[1,2] The telemetered data consisted of a sinusoid whose amplitude is a measure of $|B_\perp|$, the component of the magnetic field perpendicular to the spin axis of the vehicle. A theoretical estimate of the expected field was made by extrapolation of the surface field, using an eccentric dipole model.[3] These field estimates were combined in a computer program with the trajectory of the satellite and the orientation of its spin axis to yield expected values of $|B_\perp|$.

Figure 1 presents some representative, preliminary data for orbital sweeps occurring on August 10, August 24, and September 1, 1959. A feature which is typical of the results obtained

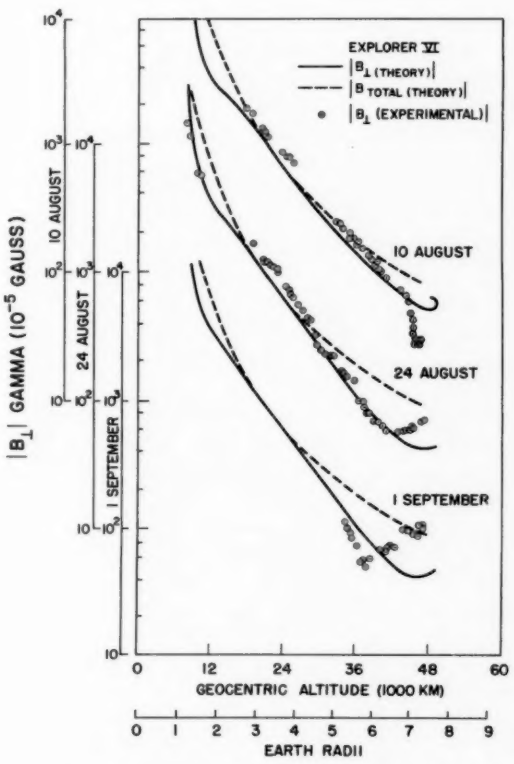

FIG. 1. Representative values of $|B_\perp|$ for ascending leg of the orbit on August 10, August 24, and September 1. The values shown in the figure are geometry dependent. The small variations shown in the inner region for August 10 and August 24 are being studied.

thus far is the reasonable agreement between the expected and the measured field at distances less than 5 to 6 R_e and the regular occurrence of large-scale deviations at greater distances. Thus, on August 10 the field displayed an abrupt, negative anomaly at $7R_e$ with indication of a field recovery with increasing altitude. On August 24, it displayed a positive-going anomaly beginning at $6.5R_e$. The data of September 1 showed a negative deviation which began at $5R_e$ and reached a minimum at $5.8R_e$. This was followed by a field increase to twice the expected value. These data were obtained on moderately quiet geomagnetic days.

It is of interest to compare these data with the results of Pioneer I[1] and the Russian cosmic rocket, Mechta.[4] In the former case, good agreement between observation and theory was obtained throughout the interval from 3.7 to 7 R_e. There is a disparity, however, between the Mechta data and the results of both Explorer VI, to this time, and Pioneer I. Neither the general depression of the field nor the anomaly at 3 to 4 R_e, which were observed by Mechta, has been detected. This disparity may disappear upon examination of more data.

The data presented in this note indicate the existence of an extraterrestrial current system beyond $5R_e$ which causes a perturbation of the geomagnetic field. It appears likely that such a current system will take the form of a toroidal ring. However, it is obvious that neither a solitary pass nor repeated orbiting which shows an anomaly in one region of the outer atmosphere constitutes unambiguous proof of annular current closure.

Figure 1 suggests the occurrence of two types of deviation and additional data, not shown, tend to bear this out. The possibility that such differences are not the result of fundamentally different kinds of current systems but are the effects of the orbital geometry is being investigated. The positive-going deviation observed on August 24 was repeated, to a lesser extent, on August 25. The deviation of September 1 occurred also on September 2, and investigation has shown that the negative-going deviation of August 10 is probably the initial portion of the same type of field variation. Figure 2 presents the amplitude of the deviation in the outer zone for August 9, August 10, September 1, and September 2. The similarity in the slopes of these curves strongly suggests similar characteristics and a similar cause for the perturbations. The data of August

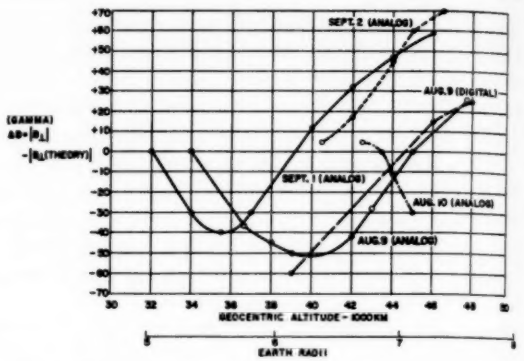

FIG. 2. The difference between the measured and expected values of $|B_\perp|$ shown for representative days. The repeatability of the slopes argues for a similar cause of the perturbations.

24 and August 25, representing the other type of deviation, have not been included so as to avoid confusion. In addition to not showing a region of decreased field, the slopes of the latter do not agree with those shown in Fig. 2.

The deviation of the type shown in Fig. 2 argues for a spatially confined current system such that a field reversal occurs as one passes through or near the current. Another obvious feature of this comparison is the difference in the altitudes at which the deviations were observed. This suggests that variations of several thousand kilometers in the location of the current system (as indicated by the position of the deviation minimum) may occur within intervals of 24 hours or less.

It is noteworthy to consider that these extraterrestrial currents appear in the region from 5 to 7 R_e. The unperturbed dipole field line through this region intersects the earth in the vicinity of the quiet day, southern auroral limit. The existence of a relationship between these currents and auroral activity is under investigation.

From the dynamics of a neutral plasma contained by a magnetic field, it is known that the individual particles will execute complex oscillations with a net drift azimuthally.[5] Because the direction of drift is charge dependent, this drift should appear as a net current flowing toroidally. Since the plasma in the exosphere is confined in just this way, convection currents capable of perturbing the geomagnetic field might be expected.[6] In addition to the large-scale deviations

discussed above, the preliminary data indicate a general increase in the magnetic field strength throughout most of the inner zone (see Fig. 1) as well as irregular deviations. Although a longitudinal drift of the total plasma field should exist and provide a current, the resultant field depression, seen by a magnetometer presumed to be interior to such a region, is difficult to evaluate and requires knowledge of the velocity distribution function for the charged particles. It does appear from the data, however, that the commonly postulated condition, $\nabla \times \vec{H} = 0$, is inadmissible in the outer atmosphere.[7]

The authors wish to thank Professor L. Davis for helpful discussions.

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MEASUREMENT OF THE GRAVITATIONAL RED SHIFT USING THE MÖSSBAUER EFFECT IN Fe^{57}

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The change in the frequency of spectral lines with gravitational potential, generally referred to as the gravitational red shift, was first predicted by A. Einstein in 1907.[1] The effect can be calculated from the time dilatation in a gravitational potential which follows from the principle of equivalence. From the point of view of a single coordinate system two atomic systems at different gravitational potentials will have different total energies. The spacings of their energy levels, both atomic and nuclear, will be different in proportion to their total energies. The photons are then regarded as not changing their energy and the expected red shift results only from the difference in the gravitational potential energies of the emitting and absorbing systems. Astronomical observations, though somewhat ambiguous, have tended to confirm this effect.[2] The recent discovery by Mössbauer[3] of recoilless nuclear resonance absorption of gamma rays as a precise resonance process has suggested to several groups[4-6] the possibility of using this effect to measure the gravitational red shift. More specifically the discovery that Fe^{57} could absorb 14.4-kev gamma rays in a resonance whose width is approximately 6.4×10^{-13} of the gamma-ray energy[4,6,7] has made this experiment a practical possibility.

We have performed this experiment using a total difference in height of 12.5 meters. A source of Co^{57} of approximately 30 millicuries was electrodeposited on the surface of an iron disk which was then heated for five hours at 700°C in a hydrogen atmosphere, then for an equal length of time in a vacuum. This disk was mounted on a transducer device which consisted of a coil mounted between the poles of an electromagnet and supported on an elastic spider. The gamma rays passed through an evacuated tube with 0.005-in. Mylar windows on both ends. Antiscattering baffles were mounted inside the tube. The detector consisted of a proportional counter with a five-inch diameter window also covered by 0.005-in. Mylar. The counter was filled with krypton gas to approximately $\frac{1}{4}$ atmosphere pressure. Krypton is especially favorable because its absorption edge is just below the energy of the 14-kev gamma rays.[8] A five-inch diameter foil containing 4 mg/cm^2 of Fe enriched in Fe^{57} to 24.1% was directly above the counter.

The transducer was driven sinusoidally at 50 cps and counts were recorded in two scalers for alternate halves of the cycle. Two other scalers were switched simultaneously and recorded tim-

ing pulses in order that small inequalities in the counting times would be corrected. The phasing of the switching pulses with respect to the motion was carefully checked and then switched through 180° at 200-minute intervals in order to cancel out systematic errors. The fluctuations in the averages of these sets of runs were subjected to a χ^2 test. For 29 data points χ^2 was 34.4, indicating that fluctuations were almost entirely due to counting statistics.

Ideally one would move the source with a constant velocity up and down, with the precise optimum value of the velocity determined by the measured width of the absorption curve and the amount of absorption. Sinusoidal motion can be easily obtained and it can be shown that such motion will be only about ~20% less sensitive to a shift in the energy of the resonance peak. In our experiment we determined that the width of the peak was 0.40 mm/sec at half maximum, considerably broader than the expected width of 0.14 mm/sec, and the maximum absorption was 18.5% in the gross counting rate. The fractional shift expected in the total energy for this height is $gh/c^2 = 1.36\times10^{-15}$. With these parameters the expected shift in the ratio of the two counting rates is 3.9×10^{-4} when the amplitude of the oscillation was 0.51 micron. The effect of the broadened peak not having a Lorentz shape was assumed to be negligible.

The amplitude of the motion on the transducer was calibrated by measurement on a microscope under stroboscopic illumination. It was monitored by a phonograph crystal pickup and is believed to be accurate to better than 10%. A total of 250 hours of counting yielded a ratio which differed from unity by 3.75×10^{-4} with an uncertainty from counting statistics of 1.76×10^{-4}. Other sources of error are believed to be negligible in comparison with this. Thus we observed 0.96 ± 0.45 times the expected shift in the energy of the gamma rays. This implies that the probability of the gravitational red shift being zero is 0.017.

The measurement was also repeated at a height of three meters to look for possible asymmetries with improved counting statistics. The result was $(0.5\pm1.0)\times10^{-4}$ where 0.9×10^{-4} was expected. The error quoted was due to counting statistics alone. Here the fluctuations in the individual runs were appreciably larger than expected from statistics. This can be largely attributed to the improved statistics of the individual runs which would emphasize short-term fluctuations, but the results indicate that these cancel out when many runs are averaged together. The statistics on this null measurement were not included in the final result.

A repetition of the experiment is intended under more favorable conditions. The accuracy in the present measurement was limited mostly by the unexpectedly great width of the peak and by the smallness of the total absorption. We hope to be able to alleviate this condition by repurifying the source and replating it under carefully controlled conditions. The source was considerably weaker than expected and contained a relatively large Co^{58} contaminant. This also contributed to the difficulties and it did not seem practical to continue the experiment under the present conditions to improve the statistical accuracy of the result.

We are greatly indebted to many individuals in connection with this work. In particular we wish to thank Professor W. C. Burcham and Professor P. B. Moon and the staff of the Birmingham Cyclotron for their generous help in preparing our source on their cyclotron. We would also like to thank Dr. Jenkins of the Radiochemical Centre, Amersham, for purifying the source; Mr. F. Hudswell and Mr. E. Furby for electroplating the source; Mr. J. H. Freeman and Mr. J. B. Reynolds for preparing the Fe^{57} absorbers, and Dr. A. D. Le Claire for providing us with facilities and advice for annealing. We are especially indebted to Dr. W. Marshall for his enthusiastic encouragement and helpful advice and to Dr. E. Bretscher and Dr. E. B. Paul for their encouragement and support. One of us would also like to thank the Atomic Energy Research Establishment for their hospitality.

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MEASUREMENT OF THE RED SHIFT IN AN ACCELERATED SYSTEM USING THE MÖSSBAUER EFFECT IN Fe^{57}

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In an adjoining paper[1] an experiment is described in which the change of frequency in a photon passing between two points of different gravitational potential has been measured. Einstein's principle of equivalence states that a gravitational field is locally indistinguishable from an accelerated system. It therefore seemed desirable to measure the shift in the energy of 14-kev gamma rays from Fe^{57} in an accelerated system. In order to do this we have plated a Co^{57} source on to the surface of a 0.8-cm diameter iron cylinder. This cylinder was rigidly mounted between two Dural plates which also held a cylindrical shell of Lucite, 13.28 cm in diameter and 0.31 cm thick, concentric with the iron cylinder. An iron foil 3.5 mg/cm^2 thick and enriched in Fe^{57} to 50% was glued to the inside surface of the Lucite. This assembly was mounted in a neutron chopper drive unit[2] and rotated at angular velocities up to 500 cycles per second. The gamma rays passing through the absorber were detected in a xenon-filled proportional counter. A schematic diagram of the apparatus is shown in Fig. 1.

The expected shift can be calculated in two ways. One can treat the acceleration as an effective gravitational field and calculate the difference in potential between the source and absorber, or one can obtain the same answer using the time dilatation of special relativity. The expected fractional shift in the energy of the gamma ray is $(R_1^2 - R_2^2)\omega^2/2c^2 = 2.44\times10^{-20}\omega^2$.

The number of gamma rays as a function of angular velocity is shown in Fig. 2. In a separate measurement the counting rate as a function of radial velocity was determined for this same source and absorber. It was found that with the source moving rapidly the counting rate was 1.29 times what it was with the source stationary. The measured full width of the resonance was 0.38 mm/sec. The curve calculated from these parameters is also shown in Fig. 2. The sensitivity of the equipment to vibrations was tested by vibrating the shaft of the rotor with frequencies corresponding to the rotational frequencies involved, and negligible effect was observed. Changes in counting rate due to forces on the absorber were also found to be negligible.

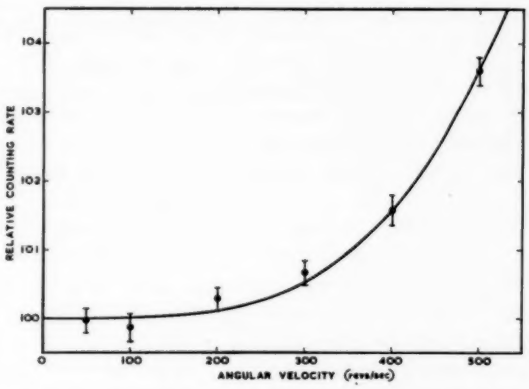

FIG. 2. Comparison of the calculated curve with experimental points. The statistical errors of each point are indicated. The curve was calculated from the parameters given in the text.

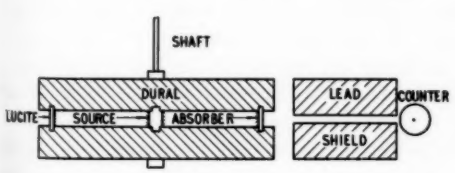

FIG. 1. Schematic diagram of the experimental equipment.

It appears that the observed effect is in reasonable agreement with expectations. The size of the shift of the gamma-ray energy in the effective gravitational field of a rotating system is in agreement with that due to the terrestrial gravitational field, within the accuracy of the measurements. The present experiment is expected to be improved when a more pure source is available for reasons stated in the previous paper. It will also be necessary to study further the factors which could influence the absorption process, including changes in the magnetic hyperfine fields due to the high velocities.

We would like to acknowledge helpful and illuminating discussions with Dr. J. S. Bell, Dr. W. Marshall, and Dr. T. Skyrme. We would also like to thank Dr. E. Bretscher for his support and encouragement.

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Argonne National Laboratory, Lemont, Illinois.

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STABLE CONFINEMENT OF A HIGH-TEMPERATURE PLASMA*

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Stable, long-time confinement of hot plasma in a "magnetic bottle" is the ultimate objective of high-temperature plasma research. Theoretically,[1-4] there are relatively few plasma-magnetic field configurations which should permit stable confinement. Even these, when experimentally tested, have until now been found to be unstable, forcing re-examination and extension of the theory. We wish in this Letter to report experiments which represent a contrary example, providing evidence for the existence of a stably confined plasma, observed under circumstances where the simplest hydromagnetic theory predicts instability.

Our two criteria for defining stable confinement are: (1) The observed confinement time shall be very much longer than the theoretically predicted exponentiation time of instabilities. (2) The rate of escape of the plasma out of the magnetic bottle shall agree reasonably with that expected from collisional diffusion (which ultimately limits the attainable time scale for any mode of plasma confinement).

To satisfy both criteria, the plasma must be hot and its particle density must not be too high. This is because rates of diffusion, being proportional to interparticle collision frequencies, become slower in a plasma the lower is its density and the higher is its temperature, whereas hydromagnetic instabilities are predicted to grow faster the higher the plasma temperature, at a rate which is essentially independent of plasma density.

In our experiments the hot plasma was confined in a Mirror Machine[5] and was produced by the adiabatic (i. e., slow) magnetic compression of a low-density burst of hydrogen plasma injected into the evacuated confinement chamber. Magnetic compression ratios ($B_{\text{final}}/B_{\text{initial}}$) of 1000 or more are used, resulting in a spindle of heated plasma typically 3 or 4 cm in diameter and about 20 cm in length. The most striking feature of this plasma is its very high electron temperature.

Following the 500-μsec compression period the magnetic field coils are short-circuited, so that the confining field decays slowly from its peak value, with a time constant of several milliseconds.

Preliminary evidence of plasma heating and long-time confinement in our experiments, first observed in 1953, was obtained by microwave methods. Subsequently the spatial and energy distribution of the confined plasma were measured and reported.[6] Typical values are:

1. Plasma particle density: initial, 10^{11} to 10^{12} cm^{-3}; compressed, 10^{13} to 10^{14} cm^{-3}.

2. Plasma electron temperature: initial, 10 ev; compressed, 10 to 25 kev.

3. Magnetic field: initial, 0 to 100 gauss; final, 10 000 to 40 000 gauss.

4. Calculated plasma β [pressure $\div (B^2/8\pi)$]: up to 0.08.

5. Observed total plasma confinement times: up to 30 milliseconds (typical half-life at peak compression, 2 milliseconds).

Confinement times and densities have been deduced by detection of x rays, by microwave radiometry and interferometry, by calorimetry, and by calculation from the initial densities, and most fruitfully by observing the time dependence of the flux of escaping fast electrons detected by scintillator plus photomultiplier placed near the magnetic axis outside one of the mirrors. (See trace of Fig. 1.) Electron temperatures were determined by absorber foils in front of

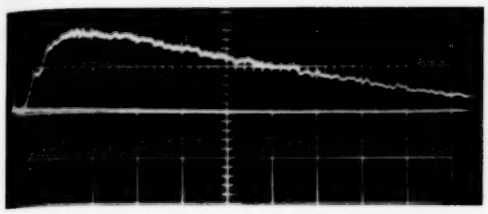

FIG. 1. Typical oscilloscope trace of a scintillator photometer signal—sweep time 5 milliseconds.

the scintillators. (See Fig. 2.) When the energy variation of the Coulomb cross section is folded into the data, a temperature for the confined electrons can be deduced. Corresponding information on ion energies is fragmentary, and largely inferential. From the necessarily low initial ion energies it can be calculated that the final mean ion energies could not be greater than 1 kev, i. e., substantially lower than the electron mean energy, a fact however, of secondary importance here. The observed confinement times are consistent within order of magnitude with those expected from collisional end losses, i. e., scattering into the escape cone.[7]

Hydromagnetic theory[1,2] predicts that a plasma confined in fields where the curvature of the field lines is for the most part concave toward the plasma (as in the Mirror Machine) should exhibit "flute" interchange instabilities essentially independent of the value of β, and of the division of plasma pressure between electrons and ions. Such instabilities would be expected to exponentiate in amplitude initially with a characteristic time constant, τ, determined by a characteristic length of the disturbance (here the length of the plasma spindle) divided by the plasma "sound" velocity $v=(p/\rho)^{1/2}$. Here $p=(n_i kT_i+n_e kT_e)$ is the plasma pressure, and $\rho=(n_i M+n_e m)$ is the plasma mass density. A lower limit to v is obtained by setting $T_i=0$, in which case $v\approx(kT_e/M)^{1/2}\simeq 1.4\times10^8$ cm sec^{-1} in these experiments. Thus a typical exponentiation time of a hydromagnetic instability would be $\tau=L/v\approx 0.14$ μsec. The growth times for other types of plasma instabilities, for example, unstable electron plasma oscillations, would be expected to be even shorter than this time. Since the observed total confinement times range up to as much as 10^5 times the longest of "instability" times, they certainly satisfy our first criterion for stable confinement.

We may estimate the "classical" rate of radial collisional diffusion across the magnetic field (e. g., Spitzer[8]). The calculated initial diffusion rate at peak compression should be approximately 0.4 cm/sec, i. e., it should be barely detectable if at all during the confinement time. This fact then poses a severe test for our second stability criterion.

Using an array of scintillators one of us (Ellis) measured the flux of escaping energetic electrons as a function of time after peak compression. At any chosen time, the variation of this escaping flux with radius measures the instantaneous value of the radial distribution of particle density. Fig. 3 presents radial particle flux distribution curves obtained by averaging over many different individual compression cycles. When these data, normalized to the same height, are corrected for the slight expansion of the magnetic flux surfaces owing to the field decay, the curves of Fig. 4 result. These data show clearly that little,

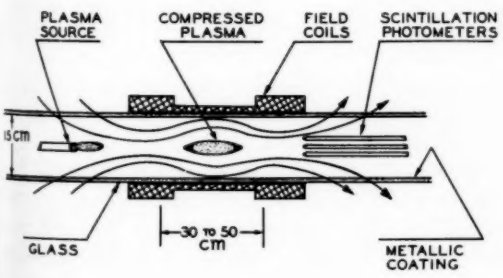

FIG. 2. Schematic arrangement of experimental apparatus.

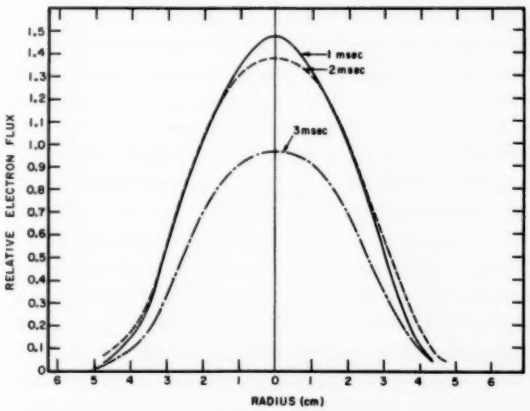

FIG. 3. Radial distribution of escaping electron flux as a function of time.

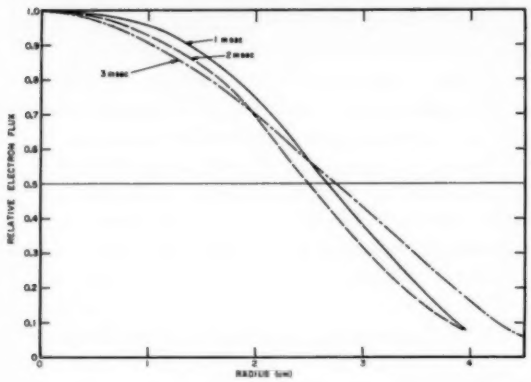

FIG. 4. Normalized radial flux distribution.

if any, radial diffusion of the bulk of the plasma electrons occurs during a period of several milliseconds after the peak compression. This conclusion is not altered qualitatively by examination of one set of traces. As analyzed by Perkins,[9] our data give a diffusion rate of 0 ± 40 cm/sec. Thus, the observations are not inconsistent with the theoretical value 0.4 cm/sec, but the statistical errors are too large to permit quantitative conclusions to be drawn. The velocity at one standard deviation is still some 10^5 times smaller than that predicted by the so-called "Bohm" diffusion formula, which might be expected to apply in the presence of intense plasma oscillations. Thus, these radial distribution measurements are not inconsistent with classical diffusion theory, and show no excessive diffusion rates of the kind which would be expected to accompany plasma turbulence.

Apparently, therefore, the plasmas obtained in these experiments satisfy the qualitative criteria defining stable confinement. Furthermore, the Van Allen radiation belt regions have many of the same features as our machine and evidently also represent a stably confined plasma.

Since the simple hydromagnetic theory predicts instability we must seek other explanations. For example:

1. Certain very special particle distributions in which most of the particles turn around near the peak of the mirrors may be theoretically stable.[3] This appears incompatible with our evidence on the plasma spatial distribution.

2. Owing to the ambipolar nature of diffusion losses from a Mirror Machine, axial and radial components of electric field can be expected to develop, which might cause differential rotation of successive flux shells of the plasma. This could be a scrambling mechanism which might inhibit flute instability growth. However, a calculation[10] of a related problem—stability of a pinch with differential rotation—indicates that this does not occur and that the effect of the rotation is to introduce another destabilizing effect—the centrifugal force.

3. The original instability calculations were done for infinite azimuthal wave number.[1,2] Due to the finite Larmor radius only perturbations with $m < \sim 10$ can be allowed in the machine. The hydromagnetic calculation can be generalized[1] to show that for low β any nonzero m would be unstable.[11] However, the more correct formulation in terms of the particle motion[2] has not yet been so generalized. It would be instructive to apply the new variational formulations[12,13] to the problem. Even these formulations are based on small Larmor radius and it remains remotely possible that in a plasma with radius about 5 times the ion Larmor radius strong additional stabilization comes about from finite Larmor radius effects.

4. Since all stability theory has been based on the linearized equations, the possibility remains that some stable configuration might be possible in which the oscillations are excited to a finite amplitude. However, since gross energetic considerations indicate that such oscillations would result in expulsion of the plasma, this explanation does not appear probable.

5. The most probable explanation for the stability is that the field lines are "tied" down outside the plasma by the metallic coatings on the chamber walls. During flute instability growth, charge separation occurs[2] in such a way that a potential difference exists between the crest and the trough of the instability. At low β only such "electrostatic" modes of growth are possible. Moreover, the fact that charges can move freely along the lines of force causes each line of force to be an equipotential. Even outside the mirror region there is likely to be enough low-density, low-temperature background plasma for this to be the case. However, the conducting end walls will not allow such potential differences to occur, but will drain charges off the flute, thus removing the electrostatic fields which drive the instability. Even an extremely thin metallic coating, such as we have, can be estimated to remove charges so efficiently that the effective growth rate is lowered from 10^7/sec to about 1/sec. Whether instabilities where growth rate is slower

than the precession around the machine can ever exist is problematical. They would certainly not be observed in these experiments.

If the purely electrostatic flute modes are thus eliminated, we must consider modes in which the magnetic field is altered in such a way that the field lines can carry the plasma out of the machine in the center, while remaining tied at the conducting end walls. In such a perturbation the plasma energy will be lowered, and the magnetic energy raised. Thus, we expect to find a critical value of β below which the plasma will be stable.[4] Calculations based on the hydromagnetic equations indicate that the critical β for our geometry is roughly 10%. More refined calculations[12,13] would be useful, but our plasma pressure is probably sufficiently low that "tying" can produce stability.

Other possible instability mechanisms must also be considered. In addition to interchange instabilities, there are other classes of instabilities which may occur in a confined plasma. These are the various "velocity-space" instabilities, e. g.:

1. The so-called "Mirror Instability" which may occur when the equilibrium plasma pressure distribution is such that the component of the pressure tensor $\perp$ to the fields is greater than that along the field lines ($p_\perp > p_\parallel$), as in a Mirror Machine. A sufficient condition for stability against this can be obtained from the work of Newcomb.[14] At any point,

$$\beta < \{\tfrac{1}{2}[(\nabla p_\perp/p_\perp)/(\nabla B/B)]+1\}^{-1}, \qquad (1)$$

the gradients being taken along the field lines. For distributions with reasonable $p_\perp/p_\parallel$ ratios, (1) is relatively large,[15] being about 0.5 in typical cases; thus it is substantially larger than our observed values. However, for highly anisotropic pressure distributions this type of instability might be very serious.

2. Unstable electron plasma oscillations, arising from anisotropies in the electron angular distribution, have been considered by Harris[16] and others. A sufficient condition for stability against this type of disturbance is that $(\omega_p/\omega_{ce})^2 < 1$, i. e., plasma frequency less than electron cyclotron frequency. Stated in terms of a lower limit critical β for the electrons, this condition is[17]

$$\beta_e < 2kT_e/mc^2. \qquad (2)$$

Although representing a serious limitation for systems of high density and low electron temperature, the high electron temperature (25 kev) achieved in our experiments means that $\beta_e \approx 0.1$, probably larger than our experimental values.

3. Unstable ion plasma oscillations. Harris[18] has also pointed out the possibility, under special circumstances (vanishing ion velocity components parallel to the field lines) of unstable plasma ion oscillations which might occur if the condition $(\omega_{pe}/\omega_{ci})^2 < 1$ is violated. This is a very restrictive condition, occurring at densities $(M/m)^2$ lower than (2) above, i. e., at densities of about 10^7 ions/cm^3. It is not clear whether the fact that we do not see these instabilities represents a contradiction with Harris' prediction or whether a more realistic ion distribution would alter the theoretical conclusions.

Since experimental stability has apparently been attained, it is worth enumerating the ways in which we differ from most other plasma heating and confinement experiments: At no time are electric fields applied parallel to the magnetic field, thus avoiding beam instabilities; adiabatic (i. e., slow) magnetic compression is used as the sole heating mechanism; and the plasma is confined by an axially symmetric externally generated magnetic field, the lines of force of which are "tied" at the ends of the machine. However, other features of our plasma differ substantially from those desired for practical application: The electrons are much hotter than the ions and the plasma dimensions are not very large compared to the ion orbit size. Moreover, at our densities the confinement times, even though in apparent agreement with theory, are still shorter by two or more orders of magnitude than those required for self-sustaining fusion reactions. This deficiency can presumably only be remedied by achieving higher ion temperatures and relying on ambipolar effects to hold the electrons. While there is no apparent theoretical reason to expect that a change in these parameters will destroy stability, nevertheless we feel that only further experiments can solve such complicated questions.

In conclusion, although we cannot as yet provide a documented theoretical explanation, we believe we have adequately demonstrated, experimentally, a case of a stably confined hot plasma. Whether the results are of general interest, or are only a special case, must be determined by additional experimentation and theoretical work. Hopefully, the experiments provide an opening wedge into

solving the problem of long-time magnetic confinement of a hot plasma.

We wish to acknowledge many helpful discussions with F. Coensgen, S. Colgate, A. Kaufman, and W. Newcomb, in addition to the past contributions of many others of the Mirror Machine group in the experimental work.

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FAR INFRARED ELECTRON-IONIZED DONOR RECOMBINATION RADIATION IN GERMANIUM

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Long-wavelength infrared radiation (~100 μ) resulting from the recombination of "hot electrons" in the conduction band of germanium with ionized donor impurities has been detected by observing the photoconductive response of a second sample of germanium. The experimental arrangement is shown in Fig. 1. All measurements were made at 4.2°K. The generator G (the sample producing the radiation) is biased at various points in the breakdown region,[1] so that the carrier density and therefore the photon output will be large. The photodetector D is below and separated from G by a Teflon window (transparent at these wavelengths[2]) so as to minimize convection currents in the helium.

No attempt was made (see Fig. 1) at a focussing geometry since everything in the cavity is either transparent or highly reflecting for 100μ radiation[2] except for the detector which is black at 100 μ and the generator which is "grey." For these conditions, a simple ergodic argument shows focussing to be unnecessary. (An earlier, unsuccessful, search for the recombination radiation, using a focussing geometry, has been reported by Braunstein.[3])

The current-voltage characteristics for a 1-ohm-cm As-doped detector for various values of current through an Sb-doped generator G are shown in Fig. 2. The experiment has been repeated with all possible permutations of Sb-doped (activation energy[4] $\epsilon = 0.0097$ ev) and As-doped ($\epsilon = 0.0127$ ev) germanium as the generator and detector. The magnitude of the photoconductive response of D is relatively insensitive to the doping agent of G, whereas the fractional response of an As-doped receiver is ~50 times greater than that of a similar Sb-doped detector.

The fact that an Sb-doped generator (with its lower value of ϵ) can induce photoconductivity in an As-doped detector indicates that the radia-

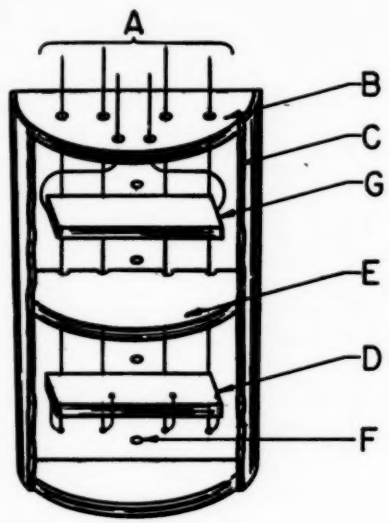

FIG. 1. Sketch of sample holder. A, Teflon-insulated copper leadwires; B, silver-slated copper chamber; C, cutaway of silver-plated cover; D, detector; E, Teflon window; F, inlet for helium; G, generator. The entire holder is inserted inside another light-tight container.

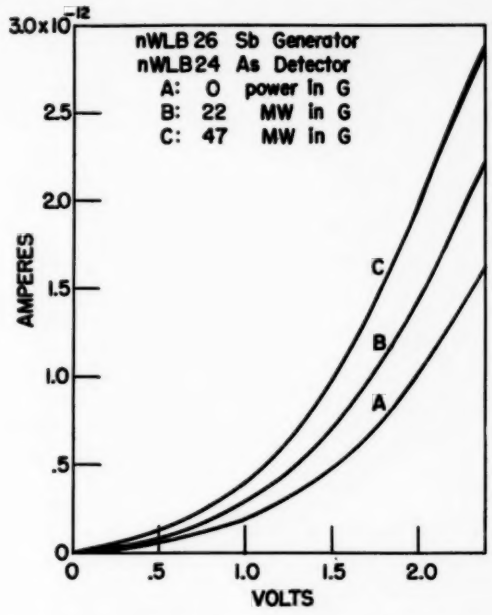

FIG. 2. A tracing of a recorder plot of the current-voltage characteristics of an As-doped detector for several values of power (in milliwatts) in an Sb-doped generator. The thickness of the tracing represents the peak to peak noise. Further data on these samples are given in reference 1.

tion must be due to recombination between reasonably "hot" electrons ($\sim 10kT$) and the donor ground state(s) (or else between unreasonably energetic electrons and an excited donor state).

There is the obvious implication here that by studying the relative response of Sb- and As-doped detectors as the electron "temperature" of G (Sb- or As-doped) is varied, it should be possible to obtain information relating to the shape of the electron distribution function in G. However, varying the bias point in the "breakdown" region of G (which may at first seem the obvious thing to do) only changes the carrier density without significantly altering the distribution (since the electric field varies very little in this range). Biasing G beyond breakdown to obtain a greater electron temperature, on the other hand, requires a prohibitively large power dissipation. It is possible, though, by using samples with differing amounts of compensating impurities, to have the breakdown occur at different electron "temperatures."[5] These experiments have yet to be done.

The sensitivity of the detector as a function of electric field E can be computed by using Price's[6] kinetic equations. If A_O is the optical generation rate of carriers in D per donor, A_T the thermal generation rate, A_I the impact ionization rate, and B_T the single electron-ionized donor recombination rate, the expression for n, the carrier density, valid for the range of Fig. 2 is

$$(A_O + A_T)(N_D - N_A) + nA_I(N_D - N_A) - nB_T N_A = 0; \quad (1)$$

$$\Delta n/n_0 \equiv (n - n_0)/n_0 = A_O/A_T,$$

where n_0 is the "dark" value of n, and N_D and N_A are the donor and acceptor concentrations, respectively. Equation (1) assumes that A_O is uniform throughout the detector, which will of course be true only in the limit $\alpha t \to 0$, where α (in cm^{-1}) is the absorption coefficient of D (proportional to $N_D - N_A$) and t the thin dimension of D. The data of Fig. 2 were taken with a photodetector which was lapped down from an initial value of $t \gg \alpha$ to one such that $t(\sim 0.3\ \text{mm}) \lesssim \alpha$, so that Eq. (1) is appropriate for this case. The value of α estimated from the measurement

of the efficiency of the infrared detection for various values of t agrees with the values reported by Fisher and Fan.[7]

From Eq. (1), it is seen that the sensitivity $(\Delta n/n_0)$ varies inversely as A_T, and therefore as $\exp(-\epsilon/kT)$. The relative sensitivities of similar Sb- and As-doped detectors at 4.2°K should then be in the ratio $\exp[(\epsilon_{Sb}-\epsilon_{As})/kT]$ ~600, assuming A_O the same for both. This factor of 600 is larger than the observed relative response (see above) of similar Sb- and As-doped detectors. It is felt that the difference is due to the fact that the As detector is responding to a smaller integrated portion of the emitted spectrum (because of its greater value of ϵ) than the Sb detector. Equation (1), in addition, predicts that $\Delta n/n_0$ should be independent of electric field (on the assumption that optically generated carriers quickly come into equilibrium with the rest of the distribution). The data of Fig. 2 are in agreement with this.

The detected power is exceedingly small. From the measured resistivity of the detector of Fig. 2 (2.5×10^{10} ohm cm), the estimated compensation and mobility[1] (~10^5 cm^2/volt sec), and from the known value of B_T,[8] A_T is estimated to be 1.5×10^{-4} (donor cm^3 sec)$^{-1}$. Knowing the detector volume and the value of (N_D-N_A) (from room temperature resistivity), one estimates that ~10^9 photons/sec or ~1.5×10^{-12} watt[9] (with a net uncertainty of a factor ~2) are being detected. A few percent of this power, judging from Fig. 2, would be the limit of detectability for the present arrangement.

It is somewhat more difficult to estimate the generated power. The optical recombination cross section has been calculated by Lampert[10] using a hydrogenic model, and discussed independently by Burstein, Picus, and Sclar.[11] Though both estimate a somewhat different cross section for the (energy-dependent) capture process, a reasonable compromise appropriate to the present situation is $\sigma\sim10^{-22}$ cm^2. This corresponds to one recombination in 10^9 being radiative.[12] For the highest power curve of Fig. 2, one estimates, from the known values of N_A (number of ionized donors), conductivity, and volume, that ~2×10^9 photons/sec or ~3×10^{-12} watt are being generated. The value of αt for the generator is ~0.1 so that the majority of the photons generated should escape (even allowing for several internal reflections). One may say, then, from the numbers, that most of the photons generated in the "grey" generator are being detected by the "black" photodetector. Consistent with this, we find that if a fraction of the cavity wall is painted with Aquadag, the detector response decreases.

A final point should be mentioned. Since the detected power is so small, an argument must be made to eliminate heating of G as the major source of the effect. For example, were G at 5°K, the integrated blackbody radiation sufficiently energetic to produce a photoconductive response in D would be ~10^{-13} watt/cm^2 (the area of G is ~1 cm^2). Were D at 4.5°K, this number (which decreases exponentially with decreasing temperature in this range) would drop to ~10^{-15} watt/cm^2. Experimentally, the response of D as a function of P, the power input to G, is linear (rather than exponential). For G biased in the breakdown region, the carrier density is proportional to P since the mobility and electric field are essentially independent of the bias current. Therefore, the photon output of G and the photoresponse of D should be linear in P.

From the published values of heat flow across an interface to liquid helium,[13] G at the maximum power input of Fig. 2 should rise to less than 0.1° above the bath ambient of 4.2°K. As a further experimental check to assure that heating of G was not contributory to the response of D, G was replaced by a 0.1-watt carbon resistor, H, of the same area and volume. H is made of a central resistive core covered by an insulating (both thermally and electrically) plastic jacket, which is presumably transparent in the far infrared. When 50 mw is dissipated in H, the core heats to ~6°K (determined from the known temperature dependence of its resistance), and there is an ~6% response of D. When the surface of H is painted with Aquadag to absorb any internally generated radiation, so that the only radiation from H will be from its surface, there is no detectable response of D. Since the germanium generator cannot support any significant thermal gradient internally, the above experiment on H conclusively demonstrates that heating of G is not responsible for the radiation reported here.

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INTERNAL IMPURITY LEVELS IN SEMICONDUCTORS: EXPERIMENTS IN p-TYPE SILICON*

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(Received December 29, 1959)

The concept of the existence of multiple sets of localized impurity levels, each associated with the various band extrema pertinent to its donor or acceptor character, has been verified by the observation of newly-found transitions to acceptor excited states in silicon lying near the split-off $p_{1/2}$ valence band maximum, within the continuum of the $p_{3/2}$ bands as shown in Fig. 1. The detection of such discrete internal impurity levels should provide information about the location of higher bands in energy-momentum space as well as about their characteristics and band parameters.

In the case of the impurity levels of the valence bands in silicon, transitions are possible between the ground state, which is primarily associated with the $p_{3/2}$ band (band a), and the excited states of the $p_{1/2}$ band (band b), as shown in Fig. 1. If we treat the coupling between the $p_{3/2}$ and $p_{1/2}$ bands as a perturbation, the transition probability from level 1 of band a to level 2 of band b has the form

$$W \propto \left[\vec{\Pi}'_{a(1)b(2)} + \frac{\mathcal{H}'_{a(1)b(1)}}{\mathcal{E}_{a(1)b(1)}} \vec{\Pi}_{b(1)b(2)} - \frac{\mathcal{H}'_{a(2)b(2)}}{\mathcal{E}_{a(2)b(2)}} \vec{\Pi}_{a(1)a(2)} \right]^2 \quad (1)$$

Here $\vec{\Pi}$ is a momentum operator between ground and excited states,[1] $\mathcal{H}'_{ab}$ is a matrix element of the effective-mass Hamiltonian connecting the two bands, and $\mathcal{E}_{ab}$ is the energy separation of the levels. Transitions are also allowed between the ground state of band b to an excited state of band a permitting, in principle, population inversion between state 2 and state 1 of band b or between state 1 of band b and state 2 of band a.

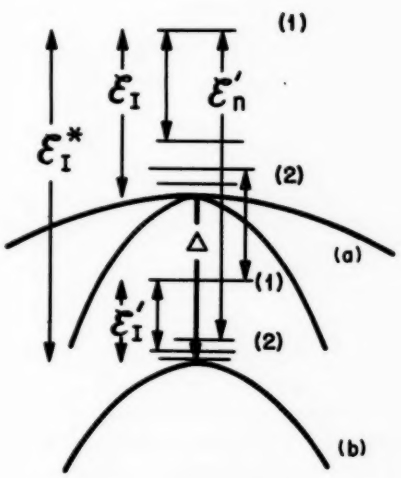

FIG. 1. Valence energy bands of silicon showing the acceptor ground state (1) and excited states (2) for both the degenerate $p_{3/2}$ bands (a) and the split-off $p_{1/2}$ band (b). The "internal" impurity levels are those nearest band b. The unlabeled arrows are also allowed transitions.

Optically-induced transitions of holes from the ground state in the forbidden gap to excited states associated with the split-off $p_{1/2}$ valence band were observed at 4°K in the wavelength range 10-15 microns using both boron- and aluminum-doped silicon. The spectra for boron-doped silicon in Fig. 2 show clearly-defined absorption maxima for transitions to the first few quantum levels, and the energies appeared to fit a Rydberg series for both boron and alumi-

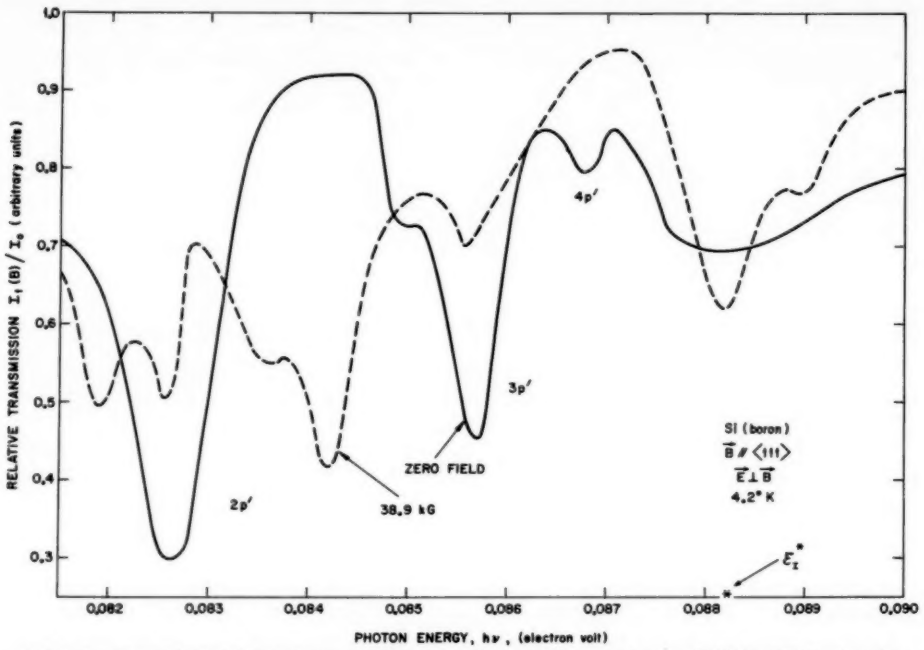

FIG. 2. Experimental spectrum obtained for the transitions at zero field (solid line) and at 38.9 kilogauss (dashed line) from the boron acceptor ground state in the gap to the internal excited states of the $p_{1/2}$ band. The ordinate scale is the ratio of the transmission through a doped sample ($t = 3$ mm, $N_A = 6 \times 10^{15}$/cc) to that of a pure sample.

num impurities in accordance with $\mathcal{E}_n' = \mathcal{E}_I^* - \mathcal{E}_I'(1/n^2)$, where $\mathcal{E}_I' = (\mathrm{ry}/\kappa^2)(m^*/m_0)$. However, it is necessary to include a correction for the nonparabolic character of the $p_{1/2}$ valence band, so that the relationship becomes

$$\mathcal{E}_n' = \mathcal{E}_I^* - \mathcal{E}_I'\left[\frac{1}{n^2} - \lambda\left(\frac{8}{3n^3} - \frac{3}{n^4}\right)\right], \qquad (2)$$

where $\lambda = [2(B^2 + \frac{1}{5}C^2)/A^2][\mathcal{E}_I'/\Delta] = 0.339$. The effective-mass Hamiltonian for the $p_{1/2}$ band was expanded to include the p^4 momentum term,[2] and then a perturbation theory calculation of the expectation value of the latter was taken using np' wave functions. The coefficient λ is essentially the dimensionless coefficient of the p^4 term. A, B, and C are the valence band parameters[3] and Δ is the spin-orbit splitting of the valence bands. In the plot of Eq. (2) shown in Fig. 3, the ordinate scale for the aluminum acceptor is shifted relative to that of the boron acceptor by just the greater depth of its gap ground state. The intercept on the energy ordinate gives directly $\mathcal{E}_I^*$(boron) = (0.0882 ± 0.0001) ev and $\mathcal{E}_I^*$(aluminum) = (0.1130 ± 0.0001) ev.

From previous infrared spectral measurements[4] on acceptor excited states in silicon, the ionization energy of holes to the $p_{3/2}$ band maximum can be estimated by extrapolating the transition photon energies to a "limit," giving $\mathcal{E}_I$(boron) = (0.0441 ± 0.0003) ev and $\mathcal{E}_I$(aluminum) = (0.0690 ± 0.0002) ev. Then the spin-orbit splitting of the valence bands in silicon[5] is

$$\Delta = \mathcal{E}_I^* - \mathcal{E}_I = (0.0441 \pm 0.0004) \text{ ev}. \qquad (3)$$

In evaluating λ for plotting Fig. 3, we have used $m^* = 0.25 m_0$ deduced from microwave cyclotron resonance results,[3] and the value of Δ obtained from a plot of the uncorrected Rydberg formula (dashed line shown in Fig. 3) in the manner described above. This determination of Δ gave the same value as in Eq. (3), and is valid since the entire Rydberg correction term vanishes as $1/n^3$ as $n \to \infty$, so that both the corrected and uncorrected plots yield the same series limit $\mathcal{E}_I^*$. From the expression for $\mathcal{E}_I'$, the hole effective mass for the $p_{1/2}$ valence band is found to be $m^* = (0.25 \pm 0.01) m_0$, where ry = 13.6 ev and a low-temperature value[6] of $\kappa^2 = 130$ have

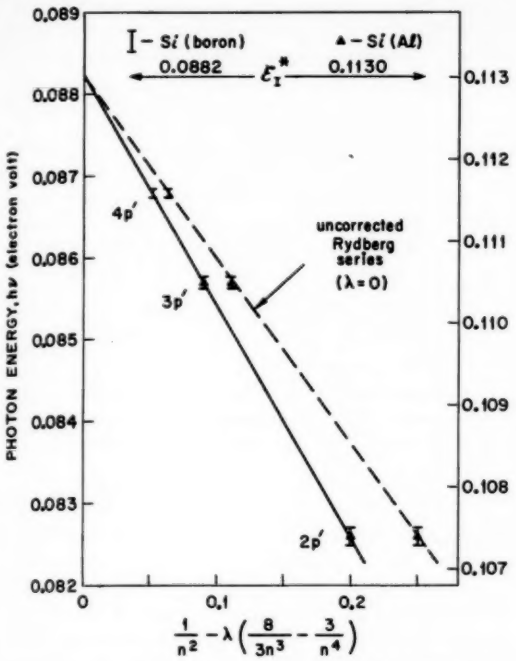

FIG. 3. Plot of Rydberg series (dashed line) and Eq. (2) (solid line) using experimental energy values for optical transitions from acceptor ground state in the forbidden gap to internal acceptor excited states for boron-doped Si (left scale) and Al-doped Si (right scale). For Si(boron), $N_A = 6 \times 10^{15}/\text{cm}^3$ and $t = 3$ mm, and for Si(Al), $N_A = 2 \times 10^{15}/\text{cm}^3$ and $t = 6$ mm.

been used. This mass value is in good agreement with the cyclotron resonance result.[3] If the p^4 term were not included, this hole effective mass would be $0.205m_0$, indicating a correction of about 20% due to the influence of the $p_{3/2}$ bands.

The Zeeman effect of these internal excited states is shown in Fig. 4 and, in addition, transitions apparently associated with bound Landau levels within the $p_{1/2}$ band are evident above $\mathcal{E}_I^*$. The spectral structure associated with the transition to the $2p'$ level is probably due to spin splitting superimposed on the Zeeman splitting. Similar spin splitting may be present in the bound Landau level spectra. Since the gap ground state presumably has a Zeeman effect also, further investigation will be needed for confirmation as well as for an evaluation of the $p_{1/2}$ band effective mass from the magnetospectroscopic data. Tentatively, the interpretation as spin splitting yields $g \approx 3$. It may also be possible to determine the sign of the valence band parameter B from this g value.

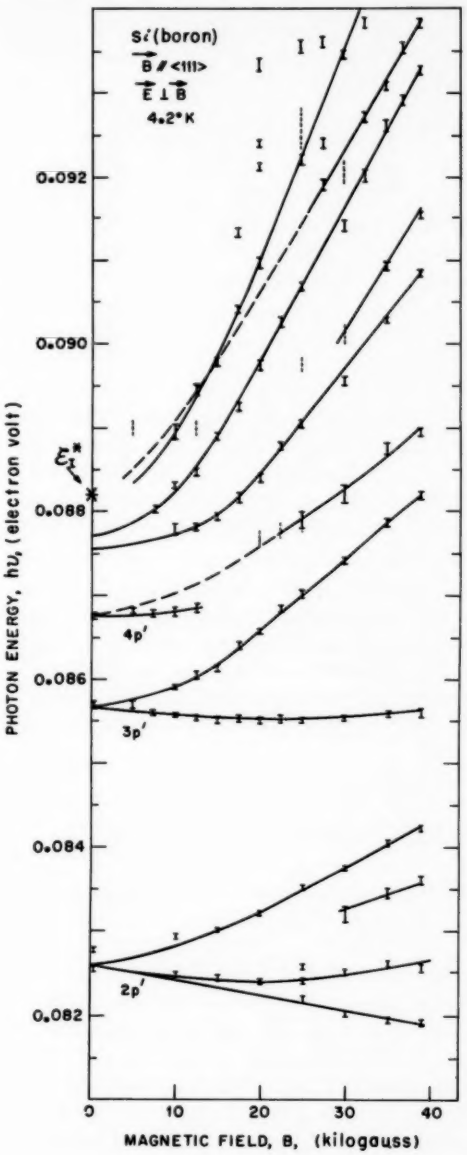

FIG. 4. Zeeman-effect energy level diagram showing the splitting of the internal impurity levels in a magnetic field. With increasing magnetic field the highest states become linearly dependent on field above the ionization limit, similar to Landau levels. The transition to the $2p'$ level shows structure probably due to spin splitting.

An analogous experiment should be possible for the valence bands in p-type germanium. Here the values of $\mathcal{E}_{ab}$ would be larger by a factor of about four, and the first term of Eq. (1)

is dominant. The transition probability should be of the same order of magnitude as in Si. Unfortunately, the absorption corresponding to this transition overlaps by ~0.01 ev the steep absorption edge of the intervalence band transition at ~0.28 ev. Nevertheless, by using an optimum impurity concentration and high spectral resolution, it may be possible to observe this transition in Ge as well as in InAs, GaAs, InP, GaP, AlP, AlAs, and AlSb where intervalence band transitions have been studied.[7]

In principle, it should be possible to observe transitions between impurity levels of bands having extrema at different values of $\vec{k}$. Such an indirect process probably involves the emission of phonons at low temperature. Thus in heavily-doped n-type Ge, transitions from the lowest $\langle 111 \rangle$ impurity level to the $\langle 000 \rangle$ and $\langle 100 \rangle$ impurity states may be observable. The former should occur at ~0.15 ev,[8] and the latter at ~0.22 ev.[9] Similarly in GaSb, a transition from the $\langle 000 \rangle$ to the $\langle 111 \rangle$ impurity level should occur at ~0.08 ev.[10] However, since the transition probability is low, impurity concentrations of the order of $10^{19}/\text{cm}^3$ may be required.

We have profited greatly from theoretical discussions with Professor G. F. Koster.

*This work was performed with the joint support of the U. S. Army, Navy, and Air Force.

[1]G. F. Koster has shown that the operator $\vec{\Pi}$ is given by $\vec{\Pi} = m_0 \nabla_p \mathcal{H}$, where $\mathcal{H}$ is either the 4×4 or the 2×2 effective-mass Hamiltonian corresponding to $\vec{\Pi}_a$ or $\vec{\Pi}_b$. The operator $\vec{\Pi}'$ is similarly obtained from $\mathcal{H}'$, which is associated with the overlapping elements of the 6×6 matrix.

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UPPER LIMIT FOR THE ANISOTROPY OF INERTIA FROM THE MÖSSBAUER EFFECT*

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The question of anisotropy of inertia has been discussed in some detail in a previous paper[1]; here we recall only that one of the consequences of Mach's principle could be that the value of the inertial mass M of a body depends on whether its acceleration is in the direction towards the center of our galaxy or in a direction perpendicular to it. The variation ΔM of mass with direction, if it exists, was found to satisfy $\Delta M/M < 10^{-9}$.

The recent discovery of the Mössbauer effect[2] has opened the possibility of comparing frequencies of γ rays, emitted by long-lived states of nuclei, with extremely high precision. The recoil-free resonant absorption of the 14-kev nuclear γ ray of Fe^{57} has already been investigated[3,4] with sufficient resolution to observe the hyperfine structure splitting in the excited state. The Mössbauer effect has been proposed as an excellent tool for detecting the gravitational red shift[5] and for many other purposes. Here we propose its use in a search for anisotropy of inertia. Precision studies of the line shapes of the Fe^{57} transition, for instance, will serve this purpose if the atomic spins can be aligned, both in the emitter and in the absorber, and the orientation of the spins relative to the direction towards the Galactic center is varied.

Consider an Fe^{57} nucleus in a nuclear state with total angular momentum quantum number J in a ferromagnetic sample with atomic spins aligned parallel to an external magnetic field. The effect of some anisotropy of inertia is then very similar to that discussed in reference 1 for the atomic Zeeman effect, except that we are now dealing with the motion of the nucleon in the Fe^{57} responsible for the γ-ray transition (at least on a shell-model picture) instead of the

motion of an electron. Let m be the magnetic quantum number referred to the magnetic field direction as axis. The interaction for each m-value with the atomic magnetic field leads to $(2J+1)$ equally spaced components of the nuclear energy level. Each component is then further shifted, if there is any anisotropy of inertia, by an amount $(\Delta M/M)\overline{T}\overline{P}_2$, where $\overline{T}$ is the average kinetic energy of the nucleon (of order 10 Mev, say) and $\overline{P}_2$ is a coefficient whose value depends on J, on $|m|$, and on the orientation of the magnetic field relative to the direction towards the Galactic center. For the nuclear ground state of Fe^{57} we have $J=1/2$ and $\overline{P}_2$ is zero. $J=3/2$ for the excited state at 14 kev and $\overline{P}_2$ is nonzero[6] for $|m|=3/2$, equal and opposite for $|m|=1/2$, and $\overline{P}_2$ changes sign as the magnetic field changes from a direction pointing towards (or away from) the Galactic center to a perpendicular direction.

The resonance absorption in the Mössbauer effect only compares the transition frequencies in the emitter and the absorber. If we neglect the magnetic moment of the Fe^{57} nuclear ground state (compared with that of the $J=3/2$ excited state), the observed pattern[3] consists of a central line plus three equally spaced satellites on each side. If the magnetic fields in the emitter and absorber are parallel to each other then the presence of anisotropy of inertia splits the first satellite into a symmetric triplet, the second satellite into a symmetric doublet, and leaves the central line and last satellite unsplit. If the two magnetic fields are perpendicular to each other, the central line is also split, into a symmetric doublet. In all cases these splittings are largest when the magnetic fields are parallel or perpendicular to the direction towards the Galactic center and vanish in between.

If the atomic magnetic fields are randomly oriented in the emitter and absorber, then the anisotropy of inertia merely contributes to the broadening of the lines. Experiments carried out so far[3,4] seem to limit this broadening to about 10^{-8} ev which already would put an upper limit of about 10^{-14} on $\Delta M/M$, the measure of the anisotropy. With small source-absorber distances the line shapes can be measured quite accurately and experiments carried out with aligned atomic magnetic fields with varying orientations relative to the Galactic center could improve the sensitivity for $\Delta M/M$ considerably.

Rather similar precision measurements will presumably be carried out by many workers in the future for quite different purposes. The present note is meant as a plea to these workers also to consider the effects mentioned above.

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*Supported in part by the joint contract of the Office of Naval Research and the U. S. Atomic Energy Commission.

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[6]$\overline{P}_2=1/5$ for a single $p_{3/2}$ nucleon.

POLARIZED SPECTRA AND HYPERFINE STRUCTURE IN Fe^{57}†

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The observation in this laboratory[1] of the polarization of the resonance radiation[2-5] emitted by the 14-kev level of Fe^{57} has led to a study of polarization in the hyperfine spectrum of the resonant absorption. The apparatus and the method of producing and detecting polarization were the same as used in reference 1 except that the source and the absorber were mounted on separate Alnico magnets. The magnet carrying the absorber was attached firmly to the bed of the lathe used in our previous work.[4] The other magnet holding the source was fastened securely to the carriage of the lathe. The detector of radiation (40-mil NaI) was mounted on the axis determined by the source and absorber and it was well shielded from magnetic fields.

The motion of the carriage provided uniform velocities of the source, and the polarized spec-

tra were obtained by measuring the transmission, with crossed or parallel magnetizations in source and absorber, as a function of the velocity of the source. The operation of the lathe was made automatic so that the carriage (source) moved to and fro at a predetermined speed. During the "to" motions the pulses from the detector were recorded in the lower channels of a 256-channel analyzer; and during the "fro" motions they were accumulated in the upper channels of the analyzer. In a single run, therefore, the transmission was measured for a positive and for an equal negative velocity.

The spectra obtained in this way are shown in Fig. 1. Since no significant differences were observed for positive and negative velocities, the spectra have been folded about zero velocity. The spectrum obtained with source and absorber magnetized perpendicular to each other differs markedly from that obtained with parallel magnetizations. For comparison, a spectrum is shown for an unmagnetized source and absorber. It is seen that the hyperfine spectrum consists of six prominent lines instead of the four previously reported.[3,5] It is clear therefore that the earlier interpretation based on the existence of only four lines is incorrect.

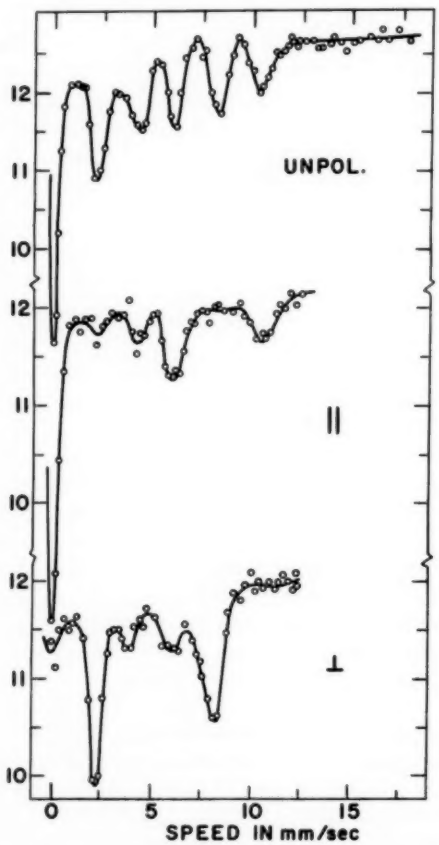

FIG. 1. Hyperfine spectra of Fe^{57}. Top: unpolarized. Middle: magnetization in source and absorber parallel. Bottom: magnetization in source and absorber perpendicular. The ordinate is in units of 2000.

The level diagram of Fe^{57} which seems to provide a satisfactory explanation of the spectra in Fig. 1 is shown on the left in Fig. 2. In the upper right are given the hyperfine components for $M1$ radiation. (We have found little need to introduce a significant amount of $E2$.) The intensities of the components are those appropriate to a random orientation of the internal magnetic fields at the nuclei. At the lower right are shown the components for the case in which the internal fields have been aligned. The intensities given are for radiations emitted perpendicular to the aligned field. The direction of polarization of each component relative to the direction of the aligned field is indicated by the symbol $\parallel$ or $\perp$.

If one takes a hyperfine pattern and moves it over itself, one obtains the hyperfine spectrum,

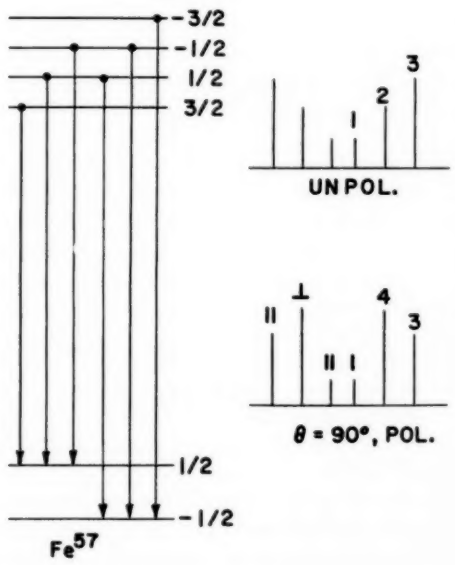

FIG. 2. Level diagram of Fe^{57} on which the discussion is based. Upper right: unpolarized hyperfine pattern. The numbers give the relative intensities. Lower right: polarized hyperfine pattern ($\theta = 90°$). The symbols $\parallel$ and $\perp$ stand for polarization parallel or perpendicular to the aligned field.

each line in the spectrum arising from the coincidence of hyperfine components in emission and absorption. At the top in Fig. 3 is shown the predicted spectrum of unpolarized radiation. In the middle is given the spectrum for the case in which the internal fields in source and absorber are aligned parallel to each other. In this case a line in the absorption spectrum will appear only if the respective hyperfine components have the same polarization. If, on the other hand, these polarizations are perpendicular, then the line will appear in the absorption spectrum only if the internal fields in source and absorber are aligned at right angles. The spectrum predicted for this case is shown at the bottom in Fig. 3. The intensities given in Fig. 3 are those nominally expected for a thin absorber. In addition it is assumed that a line which should appear only with one orientation of the fields will actually be present to the extent of about 10% with the other orientation, because of incomplete alignment of the fields in source and absorber. The spectra in Fig. 3 are in good qualitative agreement with the observations in Fig. 1.

The hyperfine pattern of six components produces, in all, eight lines in the absorption spectrum. However, the splittings in the ground state and in the excited state are such that two doublets are formed which are not resolved in the unpolarized spectrum. The resolved peaks are numbered from one to six in Fig. 3. One member of the doublet in line 2 is too weak to affect the position of the peak. Thus, the spacings between line 1 and 2, 4 and 5, and 5 and 6 should be equal to the splitting of the ground state. The spacing between lines 2 and 4 gives the splitting of the ground state. Line 3 is a doublet, one member of which should appear in the spectrum with parallel fields, the other in the spectrum with crossed fields. The separation in the doublet is equal to $2g_1 - g_0$, where g_1 and g_0 are the splittings of the excited and ground level, respectively. We have measured this doublet separation with some care by observing the shift in line 3 in going from one polarized spectrum to the other. The separation is (0.5 ± 0.1) mm/sec. We have also measured the separation between lines 1 and 2 more carefully than shown in Fig. 1 and obtained $g_1 = (2.23 \pm 0.03)$ mm/sec. Hence $g_0 = (3.96 \pm 0.10)$ mm/sec.

Ludwig and Woodbury[6] have recently obtained an accurate determination of the magnetic moment of the ground state. If we use their value of $+(0.0903 \pm 0.0007)$ nm, the above measurements

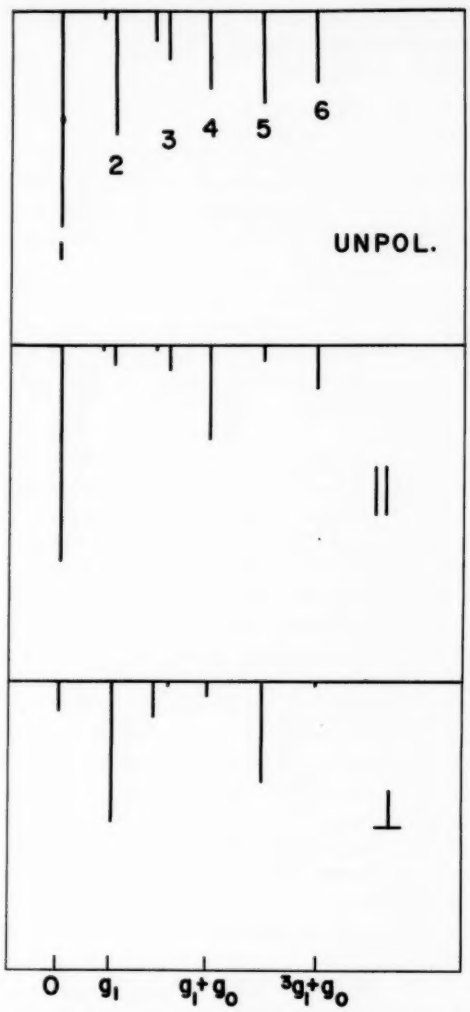

FIG. 3. Spectra predicted by the scheme in Fig. 2. Top: unpolarized. Middle: magnetizations parallel. Bottom: magnetizations perpendicular. The main peaks are numbered from one to six. The symbols g_0 and g_1 represent the gyromagnetic ratios of ground and excited levels, respectively.

give $-(0.153 \pm 0.004)$ nm for the magnetic moment of the excited state, and a value of $(3.33 \pm 0.10) \times 10^5$ oersteds for the effective magnetic field at the iron nucleus. We note the opposite sign of the magnetic moment, which is an important feature of the above interpretation.

We would like to thank B. F. Martinka and H. W. Ostrander for generous assistance in the mechanical aspects of our work. We are grateful to

G. W. Ludwig and H. H. Woodbury for communicating their results to us.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

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GAMMA WIDTH IN Be^8 PERTINENT TO A TEST OF THE CONSERVED VECTOR CURRENT THEORY*

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In a recent experimental test[1] of the conserved vector current theory of β decay it was found that the predicted $(\beta - \alpha)$ angular correlations are not observed in nuclei of mass 8. The only way this might happen and still be consistent with the theory is for the $M1$ transition width Γ_{M1} to be anomalously small between the states $(J=2, T=1)$ and $(J=2, T=0)$ in the nucleus Be^8.

The quantity Γ_{M1} enters into the predicted asymmetry coefficient for the $(\beta - \alpha)$ correlation in the form $(\Gamma_{M1})^{1/2}$. Since the $(J=2, T=1)$ level decays by α emission rather than γ emission, Γ_{M1} is not known experimentally. In the prediction[2] of the $(\beta - \alpha)$ asymmetry, a probable width of $\Gamma_{M1} = 0.15$ Weisskopf unit ≈ 8 ev was assumed.

In those cases in which a comparison has been made between experiment and calculations with the intermediate-coupling model, it is found that the computed $M1$ widths are fairly reliable. The results of calculating the Γ_{M1} pertinent to the present experiment with intermediate-coupling functions are given in Table I. Since other evidence[3] suggests that for Be^8 the intermediate-coupling parameter (a/K) lies between 2.0 and 2.5, the calculation indicates that

$$\Gamma_{M1} \approx 3 \text{ to } 5 \text{ ev}.$$

Table I. Gamma transition width Γ_{M1} for the $(J=2, T=1)$ to $(J=2, T=0)$ transition in Be^8 as a function of the relative strength of spin-orbit coupling, a/K.

a/K	0	1.5	3.0	4.5	6.0
Γ_{M1} (ev)	0	2.0	7.4	14.8	23.4

Such a value would multiply the predicted asymmetry in the $(\beta - \alpha)$ correlation by about 0.7, and thereby give a theoretical estimate of about +0.10, where the sign is determined by the positive sign of the computed matrix element. The experimental result[1] is $+0.02 \pm 0.04$. Therefore the present calculation indicates that the discrepancy between experiment and the conserved vector current theory of β decay is real.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

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TIME SPECTRA OF FILTERED RESONANCE RADIATION OF Fe^{57}†

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We report here on an experiment employing the Mössbauer[1,2] effect in Fe^{57}, which illustrates the connection between the observed rate of decay of a nuclear state and the spectrum of the radiation with which the observation is made. If the 14-kev gamma radiation from the first excited state in Fe^{57} is allowed to pass through a foil of Fe^{57} of appropriate thickness, the resonant absorption will be greater for the central frequencies than for the wings, and the transmitted line will no longer have the classical resonance shape. The latter, however, is a consequence of the Fourier analysis of a radiation amplitude which decays exponentially with the time. It was expected, therefore, that the filtered radiation would display a nonexponential time development. This effect has been observed by measuring the decay of the 14-kev state by means of the filtered radiation. The emission of the 123-kev gamma ray which feeds the state of interest was used as a time reference. The convenient half-life[3] (10^{-7} sec) of the state and the relatively large fraction (≈ 0.6 at room temperature) of nuclei which do not recoil on emission of the gamma ray make Fe^{57} an attractive choice for the experiment.

The measurements were made with a source of Co^{57} co-plated[4] with Fe^{56} on a thin copper foil, which was cemented to an aluminum disk. Absorbers of two thicknesses (0.9 mg/cm^2 and 2.7 mg/cm^2) were used as filters. These absorbers were rolled foils of Fe^{57} (isotopic abundance 75%) clamped between Lucite disks. The source and an absorber were mounted 3/4 in. apart on opposite ends of a piezoelectric transducer which consisted of a hollow tube of barium titanate. By making them vibrate with respect to each other by sinusoidally energizing the transducer, the resonance absorption could be destroyed by Doppler broadening. When the source and absorber are in relative motion, one would expect to observe the normal exponential decay, whereas when they are stationary relative to each other, the sought-after effect should be observed.

The time measurements were made with equipment previously used in the determination of lifetimes of excited nuclear states.[5] Both the 14-kev and the 123-kev gamma rays were detected in NaI(Tl) scintillators; the 14-kev detector being 3/4 in. from the absorber, and the 123-kev detector 3/8 in. from the source. Fast signals from each detector were sent to a time-to-pulse-height converter whose output was stored in a 256-channel pulse-height analyzer. The latter was gated by a slow coincidence system employing single-channel analyzers which were set to respond only to the photopeaks of the gamma rays of interest.

A typical measurement consisted of alternate vibrating and stationary runs of 4 min duration each, repeated for 48 hours. Half of the 256 channels were used to store the vibrating data; the other half, the stationary. The instrumental resolution was obtained by taking "prompt" measurements. This was done by filtering out the 14-kev radiation so that the single-channel analyzers responded only to coincidences from higher energy gamma rays from weak Co^{58} and Co^{58} contamination in the source. Decay data were also taken with no Fe^{57} absorber in place.

Figure 1 shows a prompt curve, which has a width at half-maximum of 25 mμsec. It also contains a plot of the data taken without absorber. The decay is a pure exponential with the expected half-life. (Each channel represents 8.5 mμsec.) Figure 2 is a plot of data with the Fe^{57} absorbers in place. The counting rate in the vibrating case is very nearly exponential, except for a slight concavity downward at early times. The stationary case, however, shows a decay which is by no means exponential. There is a marked early drop which shows that the resonant absorption is initially small and then increases with time. This may be explained qualitatively as follows. If one considers the exponentially decaying electromagnetic amplitude from the source in the time interval $0 < t < t_1$, it has a spectral distribution which broadens as t_1 decreases. Thus initially one should expect small resonance absorption. At later times when the spectral distribution from the source is sharper, the absorption increases.

The fact that the curve obtained with the vibrated source is not strictly exponential and approaches the curve with the stationary source at small

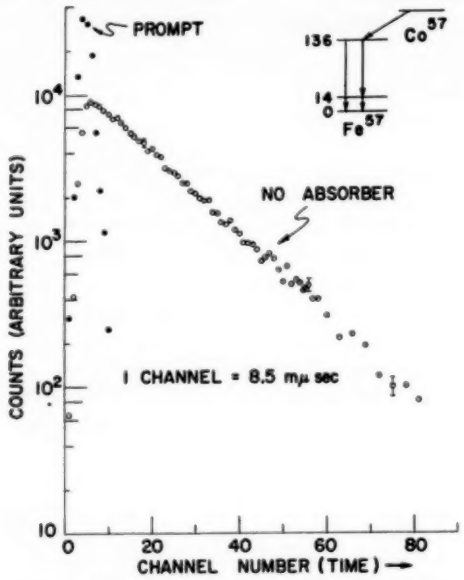

FIG. 1. A "prompt" curve, showing the time resolution, and a decay curve of the 14-kev excited state of Fe^{57}, taken without absorber to show the response of the apparatus for a normal exponential decay (1 channel = 8.5 mμsec).

times may be explained by an extension of the above argument. Since the spectral distribution is initially broad, the Doppler broadening for a given amplitude of vibration is initially less effective, and the vibrating and stationary curves (but not the curves taken with and without the resonant absorber) coalesce at small times. We have, in fact, observed that increasing the driving voltage on the transducer decreases the distortion of the curve for the vibrated source in the expected way.

A theoretical treatment based on a classical model for this phenomenon has been given by Hamermesh.[6] The results are in qualitative agreement with observations; a detailed comparison between experimental results and theory will be attempted in further work.

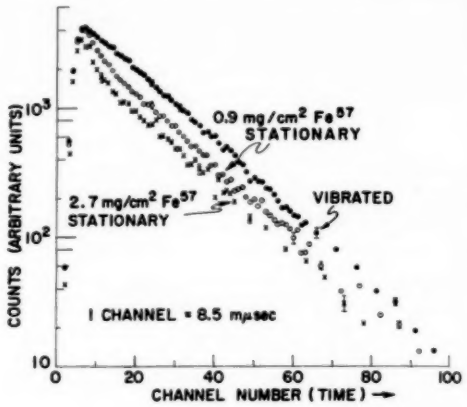

FIG. 2. Time spectra taken with source and absorber vibrated and with source and absorber stationary for two absorber thicknesses.

We are grateful to Caroline Littlejohn for stimulating discussions and to William Davidon for a number of clarifying conversations concerning the phenomenon which encouraged the authors at an early stage. We are extremely grateful to Morton Hamermesh for theoretical guidance in certain phases of the work.

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†Work performed under the auspices of the U. S. Atomic Energy Commission.

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OPTICAL MODEL POTENTIAL FOR K^- MESONS*

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The K^--meson optical model potential has long been suspected to be attractive. The strongest argument is that due to Ceccarelli et al.[1] who have considered the inelastic collisions of K^- mesons in flight with heavy nuclei. Experimental results[1-3] indicate that such collisions are very rare, K^- mesons re-emerging from the nucleus in only about 1% of the cases at 50 Mev. Ceccarelli explained this phenomenon by postulating the existence of an attractive potential. Monte Carlo calculations using the known K^--meson elastic and annihilation cross sections with nucleons confirmed that an attractive potential of some 30 Mev was sufficient to explain the rarity of such events.[4] A more direct method of determining the sign of the potential is through an optical model analysis of elastic scattering. This method was not immediately successful because of the very strong absorption of K^- mesons in nuclear matter. Essentially nuclei absorb nearly all K^- mesons which enter, the K^- mesons annihilating to form hyperons and pions. This means that the elastic scattering is rather insensitive to the central depth of any real nuclear potential. A number of early square-well optical model calculations in WKB approximation[5] were made before it was realized that the imaginary potential was large, and indications were obtained of an attractive real potential. Further exact calculations[6] using the correct imaginary potentials indicated late in 1958 that the available experimental data were not sufficient to make a decision on the sign of the nuclear potential. Recently data of much greater statistical weight in more narrowly defined energy intervals have been obtained and Jones,[7] for instance, has concluded from an analysis of events found in following 73 meters of track-length in nuclear emulsion between the energies of 105 and 140 Mev that the potential is probably attractive. The purpose of this Letter is to present a rather more detailed analysis of some new experimental results from 93 meters of track-length between the energies of 95 and 125 Mev.[8]

The experimental results were obtained by scanning along the tracks of K^- mesons in nuclear emulsion for all deflections $\geq 2°$ in the emulsion plane. The stack of emulsions was exposed to the separated K^--meson beam of the Berkeley Bevatron. The scanning was started at a residual range of 7.2 cm and ceased at a residual range of 4.5 cm, these ranges corresponding to 125 and 95 Mev, respectively. Space angles were measured for all events whose projected angle in the emulsion plane was $\geq 3°$. Geometrical corrections were applied to each individual event to allow for events excluded from measurement by this criterion. Solid angle factors to convert the number of events found per meter of track length to a cross section in barns per steradian were also applied individually to each event. Finally the events were grouped into various angular intervals and the average cross section computed in each interval. The values obtained are shown plotted in Fig. 1. It should be pointed out that the possibility of

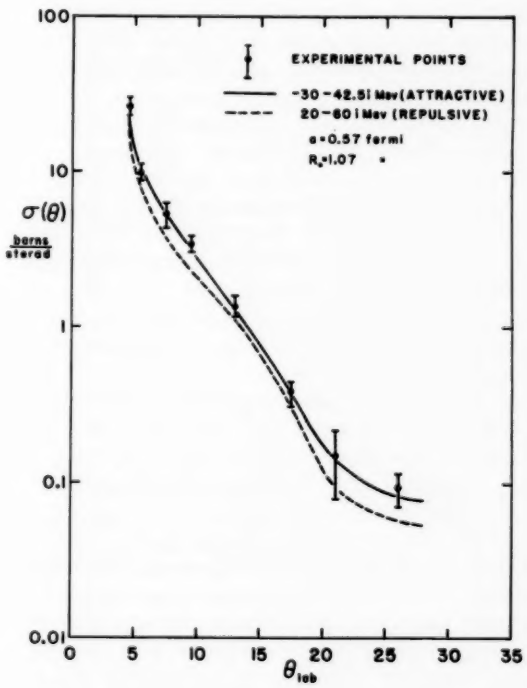

FIG. 1. Experimental angular distribution. The two curves are the theoretical curves for the potentials corresponding to the minimum and maximum values of $\sum \chi^2$ for the shape parameters given. They were obtained by plotting the theoretical averages. They do not represent a continuous differential cross section but rather the midpoints of the theoretical histograms.

direct excitation followed by the re-emission of the K^- meson has been neglected; such events would be included in the elastic category. For low momentum transfers, however, the effect is likely to be very small.

The theoretical values of the cross section were calculated from the phase shifts which were obtained by solving numerically a simplified form of the Klein-Gordon equation. The potenital adopted was of the Saxon type,[9] V, W, a, and R_0 constituting the four parameters of the diffuse-surface optical model. The computations were carried out on the IBM 709 of the Western Data Processing Center at U.C.L.A.

For given values of V, a, and R_0, the value of W is determined by the total reaction cross section. An analysis of the published data on the mean free path of K^- mesons in emulsion indicates that the best value for the reaction cross section per "average" emulsion nucleus at a mean energy of 110 Mev is 770 ± 30 mb. The statistical weight of the experimental results is insufficient to determine a or R_0, in addition to the real potential; reasonable values therefore have to be assumed for these parameters. We have chosen to carry out the analysis at two values of R_0, 1.07 and 1.20 fermis; and over a range of a values from 0.4 to 0.72 fermi. The value of the Coulomb radius was fixed at 1.07 fermis.

Because the experimental data are spread in energy from 95 to 125 Mev, for each set of optical model parameters, three calculations were made: at 100, 110, and 120 Mev; these were then averaged in the appropriate fashion. These calculations were done for two representative nuclei in the emulsion: $A=14$, $Z=7$ and $A=94$, $Z=41$, and combined in the ratio 57.4:42.6. The final result is thus an average of six individual curves—a so-called 6-run group. This result was compared with that from a 2-run group in which only one energy, 110 Mev, was considered. The differences were at all angles less than 1% and the latter half of the analysis was therefore performed using 2-run groups only. The theoretical curves were approximately integrated[10] over each angular interval and an average value thus obtained. This was then compared directly with the experimental data and values of $\sum\chi^2$ computed. Plots of $\sum\chi^2$ versus V are shown in Figs. 2 and 3 for radius parameters of 1.07 and 1.20 fermis, respectively. In all cases the value of W was chosen to exactly reproduce the reaction cross section of 770 mb. Figure 2 shows a substantial minimum in $\sum\chi^2$ in the attractive

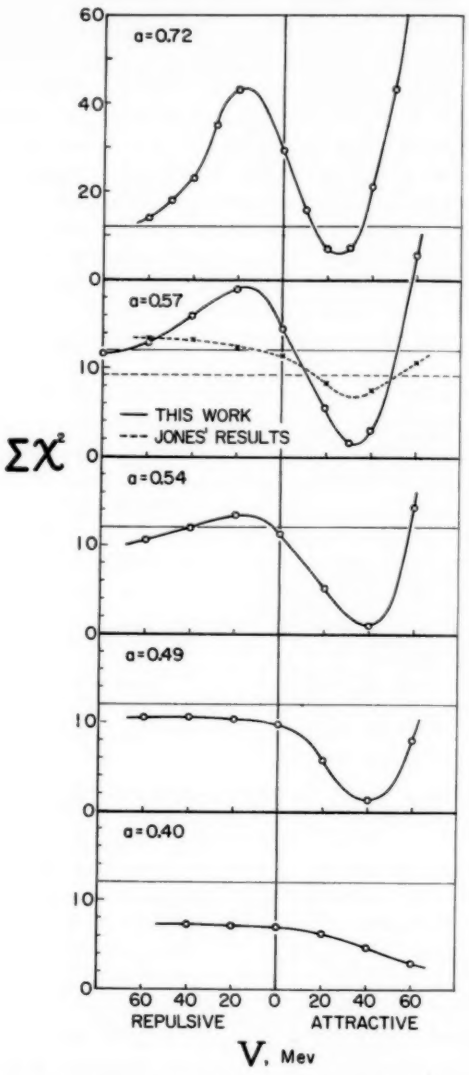

FIG. 2. Values of $\sum\chi^2$ plotted against V, the real potential, for different values of a at a constant radius of 1.07 fermis. The thin line shown at a $\sum\chi^2$ value of 12.2 is the 10% significance level.. The dashed horizontal line at $a=0.57$ is the 10% significance level for Jones' analysis.

region for all a values except the lowest, 0.40 fermi. Unfortunately this is only significant for a values of 0.54 fermi and above; below this, all potentials considered give a good fit with the experimental data, Pearson probabilities being in excess of 10%. At $a=0.57$, 10% Pearson probability limits would set the potential at a value

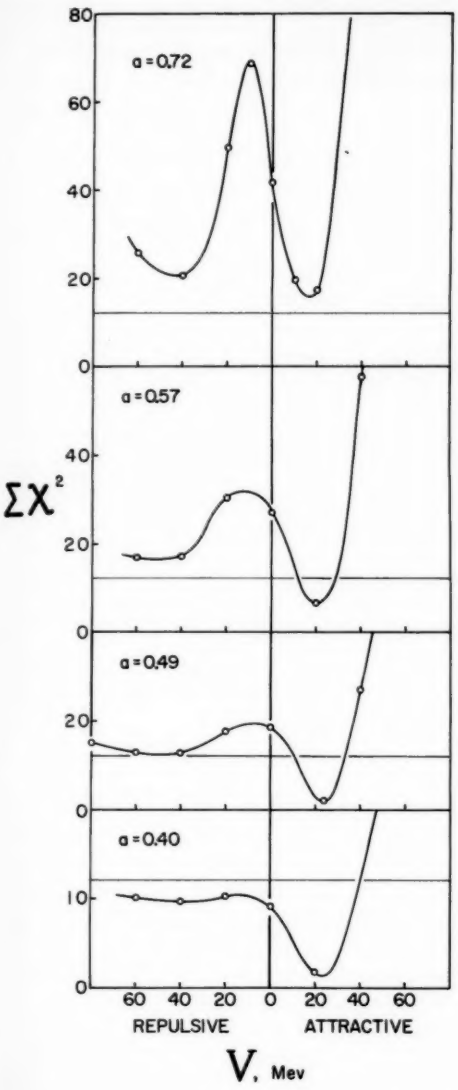

FIG. 3. Values of $\sum\chi^2$ plotted against V, the real potential, for different values of a at a constant radius R_0 of 1.20 fermis. The thin line shown at a $\sum\chi^2$ value of 12.2 is the 10% significance level.

between -5 and -50 Mev with a maximum probability of 95% at -30 Mev. This result is in agreement with the work of Jones whose $\sum\chi^2$ curve at $a = 0.57$ is also shown plotted in Fig. 2. For $a = 0.72$ fermi, the region of good fit is more restricted with the best value at -25 Mev. The situation at $R_0 = 1.20$ fermis is very similar. An attractive potential is first significantly favored at $a = 0.49$, for $a = 0.57$ the region of best fit being from -12 to -28 Mev with a best value at -20 Mev. There is no longer any potential at $a = 0.72$ which can be considered a good fit.

As the correct values of a and R_0 are not known, it is a little difficult to give a best value of V, although if a is more than 0.50 it is very likely to be attractive and most likely to be about 25 Mev. Such a potential would agree with the (a+) and (b+) s-state scattering length solutions of Dalitz and Tuan[11] and would also agree with the constructive interference found by Alvarez et al.[12] in K^--meson–proton scattering.

The authors would like to thank Professor H. K. Ticho, Dr. J. H. Mulvey, and Dr. I. E. McCarthy for discussions. They are greatly indebted to the Western Data Processing Center for the use of the IMB 709 and to Mrs. Lisa Greenstadt for help with the programming. We thank Dr. E. J. Lofgren and the Bevatron crew for making the emulsion exposure possible.

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*Partially supported by the U. S. Atomic Energy Commission and by programs of the National Science Foundation and the Office of Naval Research.

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EFFECT OF MASS SPLITTINGS ON THE CONSERVED VECTOR CURRENT*

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In order to explain the apparent lack of renormalization of the vector β-decay coupling constant, Feynman and Gell-Mann and Gerstein and Zeldovich have suggested the idea of a conserved vector current.[1] The proposed current is strictly conserved only in the approximation in which one neglects small deviations from isotopic spin conservation such as those originating from multiplet mass splittings and from the usual electromagnetic corrections. At present, the effect of these deviations is of considerable interest in view of the existence of an apparent small discrepancy between the beta and muon decay coupling constants.[2] It is the aim of this note to prove some theorems, valid to all orders in the strong coupling, concerning the effect of these mass splittings on the effective vector β-decay matrix element.

These corrections can most easily be calculated by writing an "effective" Lagrangian which consists of the usual free and strongly interacting charge-independent boson-fermion Lagrangian, L_0, the weak decay interaction L^w, plus terms involving operators which represent the multiplet mass splittings (and which, when taken between physical states, give the experimentally observed mass differences). These mass operators may be interpreted as arising from interactions which violate charge independence, such as the electromagnetic coupling, and represent the clothing by such a field of the fermion and boson propagators.[3] The total Lagrangian may be written

$$L = L_0 + L^w + L_1 + L_2,$$

$$L_1 = \tfrac{1}{2}\delta m_{n,p}\bar{N}\tau_3 N + \tfrac{1}{2}\delta m_{\Xi^0,\Xi^-}\bar{\Xi}\tau_3\Xi + \tfrac{1}{2}(\delta m^2)_{K^0,K^+}\bar{K}\tau_3 K + \tfrac{1}{2}\delta m_{\Sigma^-,\Sigma^+}\bar{\Sigma}T_3\Sigma,$$

$$L_2 = (\delta m^2)_{\pi^0,\pi^\pm}\pi^\dagger(T_3^2 - \tfrac{1}{3}T^2)\pi + \tfrac{1}{2}(\delta m_{\Sigma^0,\Sigma^+} + \delta m_{\Sigma^0,\Sigma^-})\bar{\Sigma}(T_3^2 - \tfrac{1}{3}T^2)\Sigma, \quad (1)$$

where $\delta m_{ab} = m_a - m_b$, $(\delta m^2)_{ab} = m_a^2 - m_b^2$. It should be noted that in isotopic spin space, L_0, L_1, and L_2 behave as spherical harmonics Y_0^0, Y_1^0, and Y_2^0, respectively.

The weak-interaction Lagrangian will be expressed in the form $L^w = g j_\mu^\dagger j^\mu$, where j^μ is the strangeness-conserving part of a conserved charged vector current. For the following theorems, we will assume that the part of j^μ constructed from the strongly interacting fields satisfies the condition[4]

$$\mathcal{G} j^\mu \mathcal{G}^{-1} = j^\mu, \quad (2)$$

where $\mathcal{G} = \mathcal{C}e^{i\pi T_2}$. It is not necessary to specify further the form of j_μ. In momentum space, the most general vector matrix element for β decay arising from L is of the form

$$M = [\bar{u}(p)\Gamma^\mu(q, \delta m_1, \delta m_2)u(p')][\bar{u}_e\gamma_\mu(1+\gamma_5)v_\nu], \quad (3)$$

where Γ^μ is the vertex operator

$$\Gamma^\mu = (a\gamma^\mu + bq^\mu + c\sigma^{\mu\nu}q_\nu)\tau_+,$$

and p' and p are the four-momenta of the neutron and proton, $q = p' - p$ is the four-momentum transfer, and δm_1 and δm_2 denote the various mass differences which appear in L_1 and L_2, respectively. The quantities a, b, and c are invariant functions of q^2 and of δm_1 and δm_2. The first theorem states that a and c must be even functions and b an odd function of δm_1. In order to

prove this statement let us first observe that under the transformation $\mathcal{G}$, L is changed only in that the sign in front of L_1 is reversed.

From this, it follows that under this transformation

$$\Gamma^{\mu}(q, \delta m_1, \delta m_2) \rightarrow \Gamma^{\mu}(q, -\delta m_1, \delta m_2). \tag{4}$$

On the other hand, it is possible to show by direct evaluation that under $\mathcal{G}$

$$\Gamma^{\mu} \rightarrow G\Gamma_{\mu}^{T}G^{-1}, \tag{5}$$

where $G = Ce^{i\frac{1}{2}\pi\tau_2}$. Comparing Eqs. (4) and (5) and remembering Eq. (3), we find that a and c are even functions and b is an odd function of δm_1.

The second theorem states that the contributions to M of first order in any of the δm_2 (but of zero order in the δm_1 and for $q_{\mu} = 0$) is zero to all orders in the strong coupling. In order to prove this statement we first note that the above contributions to the matrix element may be written in the Heisenberg representation in the form

$$M^{(1)} \sim \int d^4x d^4y \langle p | T\{j^{\mu}(x) L_2(y)\} | n\rangle \times e^{iq\cdot x}[\bar{u}_e \gamma_{\mu}(1+\gamma_5)v_{\nu}], \tag{6}$$

where $|n\rangle$ and $|p\rangle$ are eigenstates of the total charge-independent Hamiltonian H_0 derived from L_0.

Now we observe that $U = \int d^3x\, j^0(x)$ is a constant of the motion because j^{μ} is conserved and therefore commutes with H_0. Therefore, U acting on either $|p\rangle$ or $|n\rangle$ generates a linear combination of eigenstates of H_0 corresponding to the nucleon energy.[5] (We assume that the only possible eigenstates of this energy correspond to $i = \frac{1}{2}$.) Now, setting $q = 0$ and going to the nucleon rest frame, we notice that only the zero component of j^{μ} gives a nonvanishing contribution and $\int j^0 e^{iq\cdot x} d^3x$ reduces to U. Remembering the above-mentioned property of U and the fact that L_2, behaving as Y_2^0, cannot connect two isotopic spin $\frac{1}{2}$ states, we see that $M^{(1)} = 0$.

From the two previous theorems, we conclude that the corrections to the effective vector β-decay matrix element due to the various multiplet mass splittings may be expected to be typically of the order $(\delta m_{np}/m_N)^2 \sim 10^{-6}$. Although the corresponding corrections in O^{14} may be perhaps larger by a factor of ten because of the greater energy difference between initial and final nucleon energies, the previous results indicate that these effects may be completely neglected in determining the ratio of the muon- and β-decay coupling constants.

In a spirit of conjecture, it is perhaps interesting to observe that if it is feasible to construct appropriate strangeness-nonconserving currents which are conserved in the limit of neglecting certain baryon mass differences, then the possible existence of theorems similar to those above would indicate that the renormalization effects would be of higher order in the mass splittings than might be originally expected.

We would like to thank F. Gürsey for several stimulating discussions. One of us (R.E.B.) wishes to thank Professor J. R. Oppenheimer for the kind hospitality extended to him at the Institute for Advanced Study.

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†National Science Foundation Postdoctoral Fellow.

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STRANGENESS OF THE CASCADE HYPERON, Ξ^{-*}

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The Ξ^- hyperon has long been suspected to have a strangeness number of -2 within the framework of the Gell-Mann[1] and Nishijima[2] strangeness schemes. The experimental evidence comes both from cosmic-ray events and from events recently produced by incident K^- mesons in the Berkeley propane bubble chamber and in emulsion.[3-5] It is rather circumstantial, however, or involves events in which θ^0 mesons of undefined strangeness are produced. An example of the production and decay of a Ξ^0 hyperon has been observed by Alvarez et al.[6] The particle is observed to decay into a Λ^0 hyperon and a π^0 meson and to be produced by a K^- meson in association with a θ^0 meson. This suggests a strangeness of -2 for this neutral counterpart of the Ξ^- hyperon.

As it is not possible to define the strangeness of the θ^0 meson uniquely, one cannot balance strangeness on both sides of a reaction involving a θ^0 meson to determine the strangeness of a participant. For the successful use of the strangeness conservation law in a strong reaction, all particles involved must have uniquely defined strangeness values.

In the course of a systematic scan of an emulsion stack exposed behind the Alvarez hydrogen bubble chamber to the 1.15-Bev/c Berkeley K^--meson beam designed by Good and Ticho,[7] an event has been found which satisfies the above condition and uniquely defines the strangeness of the Ξ^- hyperon to be -2.

The emulsion pellicles were scanned for stopping K^+ mesons. Three were found and each was followed back to its star of origin. All appeared to have originated from stars produced by incident K^- mesons in the beam, but only one could be interpreted uniquely and this was also the only one in which the Ξ^- hyperon was observed.

A drawing of the event is shown in Fig. 1. The K^+ meson decays at A in the τ mode. The range of the K^+ meson is only 6.8 mm in four pellicles; the energy of the K^+ meson is therefore 32 Mev. The parent star at B consists of just 2 prongs and the primary K^- meson. The grain density of the primary appears to be about minimum in the stack and scattering measurements give a momentum (p) of 1.1 ± 0.1 Bev/c. These results are in accord with the assumption that it is indeed a

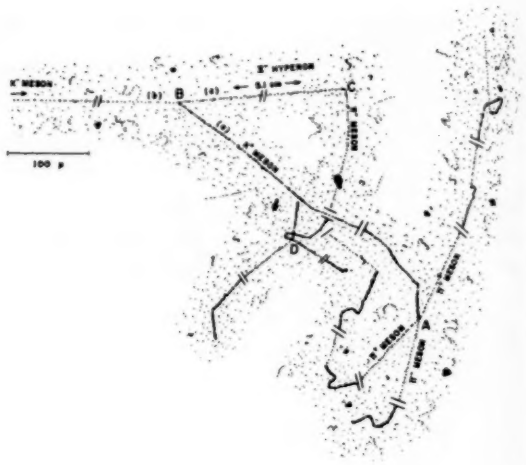

FIG. 1. Drawing of the event projected onto the emulsion plane.

K^- meson of about 1.15 Bev/c. Because the stack of pellicles was exposed behind the hydrogen bubble chamber of the Alvarez group, however, it is not possible to be certain that the energy of the beam entering the stack is exactly the same as the energy of the beam entering the bubble chamber.

The second prong from the star was followed for 5.1 cm in only 6 pellicles; it then apparently decayed at C. Scattering measurements give 906 ± 85 Mev/c for the momentum, 1.5 cm before the decay point. Grain density measurements in the fifth pellicle from the interaction, a mean distance of 0.47 cm from the decay, indicate that $g^* = 2.26 \pm 0.07$ at this point. These results support the contention that this track was caused by a Ξ^- hyperon.[8] The plate in which the ionization measurement was made was carefully normalized using the ionization of the incident K^- mesons in the beam as the standard and set equal to $1.03\times$ minimum.[8] The minimum value is considered known to $\pm 2\%$. The ionization gradient in the pellicle could introduce an additional error of 2% and the statistical error on the grain count of the Ξ^- track is $\pm 1\%$; a net error of some 3% is therefore present which introduces an error

of $^{+15}_{-12}$ Mev into the energy of the Ξ^- hyperon at the mid-point of the portion of the track counted. The energy of the hyperon at decay is thus 280^{+15}_{-12} Mev and 336^{+16}_{-13} Mev at the interaction.

The space angle between the K^--meson track and that of the Ξ^- hyperon is 6° and that between the K^+ meson and the primary, 35°. Momentum balances within the experimental error in the horizontal plane but not in the vertical plane. All three tracks in fact cross the air-emulsion surface of the pellicle containing the interaction. The momentum unbalance is 120 Mev/c. This is interpreted as indicating that the interaction is with a bound proton of about this momentum and whose direction was roughly at right angles to the primary track in the vertical plane. The angle of emission of the Ξ^- hyperon in the center-of-mass system is about 35° with the K^+ meson being emitted backwards.

The only other reasonable interpretation of the event is that the primary track is a π^- meson and that the reaction is $\pi^- + p \rightarrow \Sigma^- + K^+$. This can be ruled out by the kinematics of the decay of the Σ^- hyperon. To fit such kinematics the decay π-meson energy and the angle of emission demand that the Σ^- hyperon should have a momentum of 1.22 Bev/c at decay. This would lead to a grain density g^* of 1.51 whereas it is in fact 2.26 ± 0.07 which therefore excludes this interpretation.

The event can thus only be interpreted as the production of a K^+ meson and a Ξ^- hyperon by a K^- meson of about 750 Mev. Energy can be balanced as is shown in Table I without the supposition of any undetected neutrons. Certainly there is not energy available for the production of undetected neutral particles of nonzero strangeness. We therefore conclude that all the strange particles involved have been observed. Strangeness balance then demands -2 for the Ξ^- hyperon.

The π meson from the decay of the Ξ^- hyperon has a range of 0.85 cm contained in 10 pellicles. It came to rest and produced a typical 3-prong capture star. The angle of emission in the laboratory system is almost a right angle ($89 \pm 2°$) and since the π^--meson energy is known (21.0 Mev) and a measure of the Ξ^--hyperon energy has been obtained from ionization measurements, the decay event allows the mass of the hyperon to be deduced through the relationship:

$$E_1 E_2 - P_1 P_2 \cos\theta = \tfrac{1}{2}(M_1^2 + M_2^2 - M_N^2),$$

where E_1 and E_2 and P_1, P_2 are the energies and momenta of the Ξ^- hyperon and π^- meson, respectively, with M_1 and M_2 being their masses and M_N the mass of the Λ hyperon. θ is the angle of emission of the π^- meson in the laboratory system. Taking the values given by Alvarez[9] at the Kiev Conference, namely:

$$M_{\pi^-} = 139.63 \text{ Mev}, \quad M_{\Lambda^0} = 1115.45 \text{ Mev},$$

and solving for the mass M_1, we obtain the value of 1317.4 ± 3.4 Mev. The error comes from three sources: (1) the possible straggling error in the energy of the π^- meson, (2) the uncertainty in the Ξ^--hyperon energy, and (3) the error in the angle of emission of the π^- meson. The most serious of these is the second, but this error cannot be materially reduced by more ionization measurements on the Ξ^--hyperon track because the error is inherent in the technique and is no longer of a truly statistical nature. The value obtained is in very good agreement with the Berkeley value reported by Alvarez at Kiev.[9]

We are very grateful to Dr. E. J. Lofgren and the Bevatron crew for making the exposure possible. Professor L. W. Alvarez and Professor H. K. Ticho and Dr. M. Good are thanked for giving permission to expose the emulsion stack behind their bubble chamber while it was in operation. We thank Professor C. F. Powell and Dr. D. Evans for processing the stack in Bristol and for the loan of plates. Discussions with Dr. D. Keefe, Professor H. K. Ticho, Professor J.

Table I. Energy balance (Mev).

K^--meson mass		494	K^+-meson mass		494
K^--meson energy		750 ± 30	K^+-meson energy		32 ± 2
Proton energy		-10^{+5}_{-10}	Ξ^--hyperon energy		336^{+16}_{-13}
Proton mass		938	Ξ^--hyperon mass		1317 ± 4
	Total	2172^{+35}_{-40}		Total	2179^{+22}_{-19}

Richardson, and Professor D. Stork are gratefully acknowledged.

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*Supported in part by the U. S. Atomic Energy Commission.

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ABSTRACTS

In this section are printed the abstracts of Articles that have been forwarded to The American Institute of Physics for publication in THE PHYSICAL REVIEW. In quoting information obtained from this section before the appearance of the corresponding Article, reference should be made to "Physical Review (to be published)" rather than to this Journal.

PLASMA OSCILLATIONS OF A LARGE NUMBER OF ELECTRON BEAMS. John M. Dawson, Project Matterhorn, Princeton University, Princeton, New Jersey (Received October 27, 1959).

Longitudinal oscillations of a large number of electron beams are investigated. The normal modes for the beams are found. An orthogonality relation between the modes is obtained and is used to solve the initial value problem and the problem of forced oscillations. It is demonstrated that no signal propagates faster than the fastest beam. The problem of passing to the limit of a continuous velocity distribution is considered in detail. It is shown that in the limit the results of Landau, Van Kampen, and others are recovered. The problem of Landau damping is discussed from the point of view of the beams.

QUANTUM STATISTICS OF INTERACTING PARTICLES; THERMODYNAMIC QUANTITIES AND PAIR DISTRIBUTION FUNCTION. S. Fujita and R. Hirota, Department of Physics, Northwestern University, Evanston, Illinois (Received October 5, 1959).

An alternative approach to the quantum statistics of interacting particles is proposed. It consists of calculating the equilibrium thermodynamical quantities of the many-body system via the pair distribution function with the assumption that the particles interact with each other only through pair central forces. The proposed approach has some advantage over the usual treatment via the partition function in that the pair distribution function is easier to deal with than the partition function in certain circumstances, particularly when the collective motion description of the system is desirable. This is because only the pair distribution function can be expressed directly in terms of the collective interaction which is closely connected with collective elementary excitation such as a plasmon in the electron gas and a phonon in the hard-sphere Boson gas. The equation of state as well as the internal energy are obtained in the form of integrals of the pair distribution function. The close analogy between the pair distribution function and the two-body propagator, which appears in the quantum field theory, makes it possible to analyze the former by the use of Feynman diagrams identical with those usually introduced for the latter. The collective interaction, which is defined by the sum of the direct and the indirect interactions, is introduced as a particular partial sum of the perturbation series of the pair distribution function. This is used to rewrite the pair distribution function in terms of the collective interaction.

It is shown that while the simple chain approximation to the collective interaction in the electron gas is responsible for the transfer of a plasmon, the same approximation to the collective pseudo-interaction in the hard-sphere Boson system has a relation similar to that of transfer of a phonon, both cases occurring at low temperatures. The explicit calculation of the pair distribution functions for these systems at the absolute zero temperature is carried out up to the first order in the collective interaction (simple chain approximation). These results are used to calculate the ground-state energies. For the electron gas the energy thus obtained confirms the Gell-Mann–Brueckner calculation of the correlation energy. For the hard-sphere Bosons the calculated energy reproduces the result of Lee, Huang, and Yang. The extension of the calculation to the finite-temperature case is also indicated. In particular the classical Debye-Hückel equation of state for the electron gas is briefly discussed.

VALIDITY OF THE THEORY OF DOUBLE STREAM AMPLIFICATION. D. T. Swift-Hook, Research Laboratories, The General Electric Company, Limited, Wembley, England (Received May 18, 1959).

Misunderstandings have recently arisen concerning the validity of the original analysis of the interaction between interpenetrating ion streams to give double stream amplification.

It is shown that none of the modes of propagation upon which criticism has been centered corresponds to that of double stream amplifi-

cation.

A direct theoretical proof of the validity of the theory is given.

EXCITATION OF PLASMA OSCILLATIONS. P. A. Sturrock, Microwave Laboratory, W. W. Hansen Laboratories of Physics, Stanford University, Stanford, California (Received October 5, 1959).

The theory of Bohm and Gross and the experiments of Looney and Brown upon the excitation of plasma oscillations by the two-stream mechanism, which appear superficially to be in disagreement, are here shown to be compatible with each other and with related experiments.

IRREVERSIBILITY OF SYSTEMS PERTURBED BY RANDOM FORCES. Vernon E. Derr,* The Johns Hopkins University, Baltimore, Maryland (Received October 1, 1959).

The irreversibility of quantum mechanical systems perturbed by random forces is investigated by means of phenomenological equations derived from the Schrödinger equation. A semi-quantitative discussion depending on an assumption of time-reversal symmetry of the ensemble of random functions leads to a description of the irreversibility of a system with a finite number of states. A more general quantitative method utilizing "smoothed" density matrices produces a macroscopic description of systems tending to equilibrium states.

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THEORY OF IRREVERSIBILITY. Nobuhiko Saito,* Department of Chemistry, University of Oregon, Eugene, Oregon (Received September 4, 1959; revised manuscript received January 4, 1960).

We consider an isolated system which is exposed to external perturbations such as electric fields. The current as a linear response to a single pulse of an electric field, namely the aftereffect function, is a sum of terms periodic in time in a finite system, and does not vanish after a sufficiently long time. The transfer function is defined by the Laplace transform of the aftereffect function with respect to time and thus has poles on the imaginary axis. By applying the idea of image charges in two-dimensional electrostatic problems to a certain property of the transfer function, it is shown that, in the limit of a large system, the poles on the imaginary axis are replaced by poles in the left-half plane and consequently the aftereffect function can really vanish. This fact yields the various aspects of irreversibility. It is also shown that the complex conductivity is expressed in terms of the residues of the poles of the transfer function distributed continuously on the imaginary axis, and, in particular, that the static conductivity is proportional to the residue of the pole at the origin which never exists in a finite system but appears in an infinite system. General reciprocal relations are given for both irreversible and reversible thermodynamics, and their connection to Onsager's and Maxwell's relations are discussed. An expression for the entropy production is given and a new interpretation of the H function is proposed.

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DRIFT VELOCITY OF ELECTRONS IN NITROGEN, HELIUM, NEON, ARGON, KRYPTON, AND XENON. J. C. Bowe, Radiological Physics Division, Argonne National Laboratory, Lemont, Illinois (Received February 14, 1958; revised manuscript received July 27, 1959).

Accurate values of electron drift velocity in purified noble gases and nitrogen have been obtained by measuring the transit time of photoelectrons across the gap of a parallel-plate condenser. Drift velocities in pure krypton and xenon have not been measured before. The values obtained for the other gases are invariably lower than those reported by Nielsen, the discrepancy for neon being large. The sharp maximum found by English and Hanna for argon at $E/p_0 < 0.1$ and tentatively ascribed by them to the Ramsauer effect was not observed in the purified gas.

TRANSPORT COLLISION CROSS SECTIONS FROM ELECTRON DRIFT-VELOCITY DATA. J. C. Bowe, Radiological Physics Division, Argonne National Laboratory, Lemont, Illinois (Received July 27, 1959; revised manuscript received October 22, 1959).

Information concerning the transport collision cross section $\sigma_t(\epsilon)$ of low-energy electrons in

the noble gases was obtained from drift-velocity data. The results (with ϵ in ev) are as follows:

He: $\sigma_i(\epsilon) = (28 \pm 1)\ \mathrm{cm}^{-1}$ for $0.13 \leq \epsilon \leq 4$;

Ne: $\sigma_i(\epsilon) = (6.05)\,\epsilon^{0.157}\ \mathrm{cm}^{-1}$ for $0.38 \leq \epsilon \leq 8$;

A: $\sigma_i(\epsilon) = (6.3 \pm 0.6)\,\epsilon\ \mathrm{cm}^{-1}$ for $1.6 \leq \epsilon \leq 11$;

Kr: $\sigma_i(\epsilon) = 14\,\epsilon\ \mathrm{cm}^{-1}$ for $1.6 \leq \epsilon \leq 3$;

Xe: $\sigma_i(\epsilon) = 26\,\epsilon\ \mathrm{cm}^{-1}$ for $1 \leq \epsilon \leq 2.4$.

All σ_i values are for 0°C and 1 mm Hg pressure. These results are compared with other experimental and theoretical data. For nitrogen the drift-velocity measurements indicate an average fractional energy loss per collision of $20(2m/M)$ in the energy range $\epsilon = 0.07$ to 0.15 ev.

PARAMAGNETIC RESONANCE OF Ni^{++}, V^{++}, AND Cr^{+++} IN ZnF_2. Martin Peter and J. B. Mock, Bell Telephone Laboratories, Murray Hill, New Jersey (Received October 21, 1959).

The millimeter-wave paramagnetic resonance spectra of Ni^{++}, V^{++}, and Cr^{+++} have been measured in ZnF_2. Evidence was found that the extra charge of Cr^{+++} is compensated by an F^- ion, sitting on one of two available nonequivalent neighboring sites. The antiferromagnetic resonance line in NiF_2 which has been postulated by Moriya is now expected to occur at 320 kMc/sec.

SPACE-CHARGE FIELDS IN $BaTiO_3$. S. Triebwasser, Research Laboratory, International Business Machines Corporation, Poughkeepsie, New York (Received October 22, 1959).

Experiments have been performed in which observations have been made in the presence of dc electric field bias of (1) hysteresis loops, (2) double loops above the Curie point, (3) Kerr electro-optic effect above the Curie point, and (4) capacitance above the Curie point in $BaTiO_3$. The purpose of these experiments was to determine field distributions in the crystal under an externally applied difference of potential and to examine the extent to which space-charge surface layers cancel the bulk field. The first three types of observations were qualitative in nature. The biased hysteresis loops show normal behavior with no evidence of field cancellation. Double loop measurements show some evidence of field cancellation, while Kerr electro-optic measurements show strongly nonuniform fields indicating anomalous space-charge fields. The measurements of capacitance above the Curie point indicate that surface layers build up in the presence of a dc field, and these surface layers have a capacitance that varies with applied voltage. The results can be understood qualitatively if simple Schottky exhaustion barriers are assumed at the two metal electrode-crystal contacts. Observed asymmetries with respect to the applied fields are discussed.

THEORY OF MAGNETISM AND THE GROUND-STATE ENERGY OF A LINEAR CHAIN. David I. Paul, Department of Physics, University of California, Los Angeles, California (Received October 5, 1959).

The theory of strong magnetic effects is investigated from the point of view of orthogonal atomic functions for the case of one dimension. Thus, the exchange integral is considered positive and the interaction between the polar and the nonpolar states for all possible arrangements of electron spins is included in our formulation of the problem. The resulting secular equations are solved for both large and small interactions between states for the case of only one electron spin oriented in a direction opposite to all other electron spins, and they are solved for small interactions between states for the more general case of any number of electron spins being in a given direction. It is shown how inclusion of the polar states can yield either a ferromagnetic or an antiferromagnetic ground state depending on the difference in absolute magnitude between the exchange integral and the sum of other integrals representing electron-nuclei interactions.

STRAIN SCATTERING BY VACANCIES AND IMPURITIES IN METALS. P. M. Lee* and N. H. March, Department of Physics, The University, Sheffield, England (Received October 20, 1959).

A simple model is proposed by means of which nearest-neighbor displacements round a vacancy and an impurity in a metal may be taken into account in calculating excess resistivities. Using Tewordt's calculated nearest-neighbor displacement for a vacancy in copper, we obtain from

our model an excess resistivity of 0.9 μohm cm per atomic percent. The same model without strain yields 0.97 μohm cm. The case of silver impurities in copper is also considered and it is shown that a radial increase of ~3% in the nearest-neighbor distance is sufficient to account entirely for the observed excess resistivity.

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SPIN RESONANCE OF V^{2+}, V^{3+}, V^{4+} IN α-Al_2O_3. John Lambe and Chihiro Kikuchi, Willow Run Laboratories, The University of Michigan, Ann Arbor, Michigan (Received October 22, 1959).

The electron-spin resonance absorption properties of vanadium sapphire are reported. It is shown that normally vanadium is predominantly trivalent with a small amount in the tetravalent state. After irradiation by x rays or gamma rays, vanadium is converted to the divalent state. The hfs component separations for V^{2+}, V^{3+}, and V^{4+} are about 88, 110, and 140 gauss, respectively. Because of its readily recognizable spin resonance signature, due to its nuclear spin and because of the ease of producing different oxidation states, it is suggested that vanadium may be a suitable probe to study ionization effects in certain solids.

NEUTRON DIFFRACTION STUDY OF THE MAGNETIC PROPERTIES OF RARE EARTH IRON PEROVSKITES. W. C. Koehler, E. O. Wollan, and M. K. Wilkinson, Oak Ridge National Laboratory, Oak Ridge, Tennessee (Received October 16, 1959).

A neutron diffraction study has been made of the magnetic properties of the rare earth iron perovskites, $NdFeO_3$, $HoFeO_3$, and $ErFeO_3$, at temperatures ranging from 955° to 1.25°K. The iron ions in each of these compounds undergo a transition to an antiferromagnetic configuration in which each moment has six oppositely directed moments at nearest neighbor distances. The Néel temperatures are 760°K, 700°K, and 620°K, respectively, for the compounds of Nd, Ho, and Er. The moment directions in $HoFeO_3$ and $ErFeO_3$ are parallel and antiparallel to the orthorhombic [100] direction at room temperature: at 43°K the moments are found to be in a $(1\bar{1}0)$ plane. In $HoFeO_3$ the iron ion moments at 1.25°K are parallel to [001]; in $ErFeO_3$ at the same temperature they are parallel to [110]. The magnitudes of the ordered iron moments at temperature saturation are 4.5_7, 4.6_0, and 4.6_2 Bohr magnetons in $NdFeO_3$, $HoFeO_3$, and $ErFeO_3$, respectively. In the liquid helium temperature range, magnetic ordering transitions of the rare earth ions in $HoFeO_3$ ($T_N = 6.5$°K) and $ErFeO_3$ ($T_N = 4.3$°K) are observed. The Er^{+3} ion moments form a nearly ideal antiferromagnetic configuration in which a chain of parallel moments is surrounded by four chains of oppositely directed moments at nearest neighbor distances. In this compound the Er^{+3} ion moments are parallel and antiparallel to [001] and at 1.25°K have a magnitude of 5.8 Bohr magnetons. In $HoFeO_3$ the ions are ordered in a distorted antiferromagnetic configuration in which, at 1.25°K, each Ho^{+3} moment with magnitude of 7.5 Bohr magnetons makes an angle, in the (001) plane, of about 27° with the [010] direction so as to produce a net ferromagnetic moment of 3.4 Bohr magnetons per $HoFeO_3$ molecule parallel to [100].

HARMONIC SPIN COUPLING IN RUBY. J. E. Geusic, Bell Telephone Laboratories, Murray Hill, New Jersey (Received October 19, 1959).

A new mode of maser pumping which makes use of harmonic spin coupling in ruby has been demonstrated. In addition higher order harmonic spin-coupling effects in ruby have been found experimentally.

INFRARED LATTICE ABSORPTION OF GaP. D. A. Kleinman and W. G. Spitzer, Bell Telephone Laboratories, Murray Hill, New Jersey (Received October 29, 1959).

Transmission and reflectivity measurements on GaP in the wavelength region 1 to 40 μ have been analyzed to obtain information on the lattice vibrations. The fundamental reflection band has been fitted by dispersion theory and the strength, width, and resonance wavelength (27.3 μ) determined. The dielectric constant is found to be 8.5 ± 0.2 in the range $1 < \lambda < 12$ μ and 10.2 ± 0.2 for $\lambda > 40$ μ. The background absorption in n-type samples due to free carriers was reduced by copper diffusion to make possible accurate transmission measurements of the lattice combina-

tion bands. An assignment scheme using five frequencies is proposed to explain the combination bands. The temperature dependence of the bands is consistent with theory for two-phonon processes. One band is observed which appears to be due to molecular vibrations of an impurity not yet identified. From the integrated absorption it is concluded that the principal mechanism for the combination bands is the anharmonic potential energy.

ANHARMONIC FORCES IN THE GaP CRYSTAL. D. A. Kleinman, Bell Telephone Laboratories, Murray Hill, New Jersey (Received October 29, 1959).

The infrared properties and the thermal expansion of gallium phosphide are treated on the basis of a simple model of the anharmonic forces. In this model the anharmonic forces are nearest neighbor central forces characterized by a single parameter. The value of this parameter for GaP is obtained from the integrated absorption recently measured for certain infrared combination bands. It is shown that the observed width of the fundamental resonance (reststrahl) and the observed shift with temperature of the combination bands are consistent with the absorption. This is presented as evidence that the anharmonic mechanism is predominantly responsible for the infrared absorption in the combination bands. It is also shown that the observed thermal expansion is consistent with the same anharmonic model.

PARAMAGNETIC RESONANCE OF IMPURITIES IN $CaWO_4$. TWO S-STATE IONS. C. F. Hempstead and K. D. Bowers, Bell Telephone Laboratories, Murray Hill, New Jersey (Received October 26, 1959).

Paramagnetic resonance measurements have been made on Mn^{2+} and Gd^{3+} ions in single crystals of $CaWO_4$ grown from the melt. In both cases the four different possible substitutional sites in the unit cell lead to identical resonance spectra with tetragonal symmetry. The splitting of the electronic levels in zero magnetic field is much greater for Gd^{3+} than for Mn^{2+}, e.g., the expansion parameter b_2^0 is 6.7 times greater and b_4^4 is 13 times greater. The large value of b_2^0 (-0.0917 cm^{-1}) for Gd^{3+} makes it a potentially useful material for three-level masers. The lines are narrow, and the hfs due to $Gd^{155,157}$ is well resolved: the ratio of coefficients, A^{155}/A^{157}, was determined to be 0.763 ± 0.006.

CRITICAL FIELD CURVE OF SUPERCONDUCTING MERCURY. D. K. Finnemore, D. E. Mapother, and R. W. Shaw, Physics Department, University of Illinois, Urbana, Illinois (Received October 26, 1959).

The critical field curve of mercury has been precisely measured in a range of reduced temperature, $t = T/T_c$, from 1 to 0.27. The observed H_c values show an appreciable deviation from a parabolic temperature dependence, lying above the parabola which passes through the experimental values of H_c and T_c. The general behavior is similar to that previously observed in the case of lead. Values of the temperature coefficient of the normal electronic specific heat, γ, are derived, but are somewhat uncertain since the H_c data indicate an appreciable entropy contribution from the superconducting electrons at the lowest temperature of measurement. The qualitative behavior of $H_c(T)$ for lead and mercury is in accord with recent infrared measurements which give direct indication that the energy gap value for these elements is anomalously large.

EFFECT OF THE LATTICE ON DIELECTRIC PROPERTIES OF AN ELECTRON GAS. David S. Falk,* Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts (Received October 19, 1959).

A system of N electrons in the presence of a rigid periodic background of positive charge is considered. Following Martin and Schwinger, an inverse dielectric operator, $\mathcal{K}'$, is introduced. An approximate equation which takes into account the long-range nature of the Coulomb field is derived for $\mathcal{K}'$. A representation is used where $\mathcal{K}'$ is a matrix with rows and columns labeled by vectors of the reciprocal lattice. Poles and zeros in the dielectric operator are found to be manifestations of Bragg's law. Assuming these to be the major effect of the lattice, the equation for $\mathcal{K}'$ is solved. The result is examined in the weak-binding limit and seen here, except at the Bragg reflections, to agree with that of Nozières

and Pines. Finally the ground-state energy of the system is exhibited.

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HELICAL SPIN ARRANGEMENT IN CHROMIUM METAL. B. R. Cooper, Department of Physics, University of California, Berkeley, California (Received October 29, 1959).

The lowest energy spin arrangements in a body-centered cubic crystal with first, second, and third nearest neighbor exchange interactions are given. The results may explain the experimental neutron diffraction pattern for chromium single crystals as observed by Corliss, Hastings, and Weiss. The susceptibility of the helical array is calculated.

ANOMALOUS EFFECTS OF DOUBLE EXCHANGE IN MAGNETIC CRYSTALS. P.-G. de Gennes,* Department of Physics, University of California, Berkeley, California (Received October 9, 1959).

This paper discusses some effects of mobile electrons in some antiferromagnetic lattices. It is shown that these electrons (or holes) always give rise to a distortion of the ground-state spin arrangement, since electron transfer lowers the energy by a term of first order in the distortion angles. In the most typical cases this results in (a) a nonzero spontaneous moment in low fields, (b) a lack of saturation in high fields, (c) simultaneous occurrence of "ferromagnetic" and "antiferromagnetic" lines in neutron diffraction patterns, and (d) both ferromagnetic and antiferromagnetic branches in the spin wave spectra. Some of these properties have indeed been observed in compounds of mixed valency such as the manganites with low Mn^{4+} content. Similar considerations apply at finite temperatures, at least for the (most widespread) case where only the bottom of the carrier band is occupied at all temperatures of interest. The free energy is computed by a variational procedure, using simple carrier wave functions and an extension of the molecular field approximation. It is found that the canted arrangements are stable up to a well-defined temperature T_1. Above T_1 the system is either antiferromagnetic or ferromagnetic, depending upon the relative amount of mobile electrons. This behavior is not qualitatively modified when the carriers which are responsible for double exchange fall into bound states around impurity ions of opposite charge. Such bound states, however, will give rise to local inhomogeneities in the spin distortion, and to diffuse magnetic peaks in the neutron diffraction pattern. The possibility of observing these peaks and of eliminating the spurious spin-wave scattering is discussed in an Appendix.

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THEORY OF THE VALENCE BAND STRUCTURE OF GERMANIUM IN AN EXTERNAL MAGNETIC FIELD. R. F. Wallis and H. J. Bowlden,* U. S. Naval Research Laboratory, Washington, D. C. (Received October 30, 1959).

The energies of the magnetic sub-bands associated with the V_1 and V_2 valence bands in germanium have been calculated as a function of k_z, the propagation constant parallel to the external magnetic field. Warping of the V_1 and V_2 bands was neglected. Sub-bands belonging to the 1^+ and 2^+ ladders (light holes) have minima at $k_z = 0$ and show quantum effects consisting of a decrease in curvature as the valence band edge is approached. Sub-bands belonging to the 2^- ladder (heavy holes) also have minima at $k_z = 0$, but the curvatures increase near the valence band edge. The 1^- heavy-hole sub-bands show very marked quantum effects. The sub-band minima occur at values of k_z different from zero, and local maxima appear at $k_z = 0$. The peculiar nature of the 1^- magnetic sub-bands may lead to observable effects in various magneto-optic phenomena in germanium.

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NUCLEAR MAGNETIC RESONANCE IN ANTIFERROMAGNETIC MnF_2 UNDER HYDROSTATIC PRESSURE. G. B. Benedek and T. Kushida,* Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts (Received October 23, 1959).

The nuclear magnetic resonance frequency of the F^{19} nucleus in antiferromagnetic MnF_2, in zero external field, has been measured as a

function of pressure at 4.2°K, 20.4°K, and 35.7°K using a new-type very high frequency variable-frequency spectrometer. From these measurements we have deduced the pressure dependence of the hyperfine coupling constant (A) between the manganese electrons and the fluorine nucleus, and the pressure dependence of the Néel temperature. This deduction gives $(1/A)(dA/dP) = +(1.9 \pm 0.1) \times 10^{-6}/(\text{kg/cm}^2)$ and $(1/T_N)(dT_N/dP) = +(4.4 \pm 0.3) \times 10^{-6}/(\text{kg/cm}^2)$. We have also measured the compressibility of MnF_2. The magnitude and pressure dependence of A is explained using the theories of Mukerji and Das, and Marshall and Stuart, which permit a calculation of the dependence of A on the interatomic distances, starting from the Hartree-Fock self-consistent field wave functions for Mn^{2+} and F^- with the Mn^{2+} wave functions properly adjusted to bring it into agreement with neutron scattering form factor measurements. The theory is in very good agreement with the experimental results.

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GENERALIZATION OF BAND THEORY TO INCLUDE SELF-ENERGY CORRECTIONS. G. W. Pratt, Jr., Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts (Received October 28, 1959).

A one-particle Schrödinger-like equation is found whose eigenvalues in certain cases are identical with the energies of the many-electron states of a semiconductor or insulator including self-energy corrections. The one-particle Hamiltonian is expressed in terms of the Coulomb interaction as modified by polarization processes. The relation is given between the modified Coulomb interaction and the dielectric function which is the generalization of the classical dielectric constant. Suggestions are made as to how the one-particle equation including self-energy effects might be solved in practice.

ELECTRIC-FIELD-INDUCED LIGHT ABSORPTION IN CdS. Richard Williams, RCA Laboratories, Princeton, New Jersey (Received October 13, 1959).

It has been found that a significant shift in the wavelength of the absorption edge of CdS may be produced by applying an electric field to the rectifying junction between a conducting CdS crystal and an electrolyte solution. An applied voltage of 120 volts shifts the absorption edge to longer wavelengths by 70 A. The effect is reversible and when the field is removed the absorption edge returns to the wavelength it had before the field was applied. It is believed that the enhanced absorption produced by the field is the result of photon-assisted tunneling of electrons from the valence band to the conduction band in a high-field region of the crystal near the electrolyte interface.

SURFACE IMPEDANCE OF A SUPERCONDUCTOR IN A MAGNETIC FIELD. G. Dresselhaus and M. Spiewak Dresselhaus, Laboratory for Atomic and Solid State Physics, and Department of Physics, Cornell University, Ithaca, New York (Received October 26, 1959).

Explicit expressions for the static magnetic field variation of the surface impedance in a superconductor are derived. Detailed consideration is given to the two limiting cases of the classical skin effect and of the extreme anomalous skin effect, with the static field either parallel or perpendicular to the rf current. The transport calculation is carried out for a two-fluid model with the supercurrent obeying the London equation and the normal current following a nonlocal relation. It is suggested that a comparison between theory and the experimental data yields information on the energy band structure of normal electrons in the superconducting state.

SPECIFIC HEAT OF CHROMIUM-IRON ALLOYS AT ROOM TEMPERATURE. K. Schröder, University of Illinois, Urbana, Illinois (Received October 5, 1959).

The specific heat of body-centered cubic iron-chromium solid solution alloys was measured at room temperature and then calculated under simplified assumptions from lattice, magnetic, and electronic terms. The magnetic atomic heat was evaluated using the simple Weiss theory. The electronic term was assumed to be equal to γT, where the value of γ used was that obtained earlier from low-temperature specific heat measurements. The lattice term was taken to

be the same for all alloys. Reasonable quantitative agreement between the calculated and the measured values was achieved.

SOME EFFECTS OF NEUTRON BOMBARDMENT ON MgO CRYSTALS. William C. Schieve, Martin A. Pomerantz, and Romas A. Shatas,* Bartol Research Foundation of the Franklin Institute, Swarthmore, Pennsylvania (Received May 6, 1959; revised manuscript received December 2, 1959).

Electrical conductivity and post-bombardment conductivity induced in MgO crystals by electron irradiation have been investigated following exposure to neutrons in the Brookhaven pile (integrated epicadmium fluxes of 4.2×10^{16} n/cm^2 and 5.1×10^{17} n/cm^2, respectively.) A change in carrier lifetime was observed. No change in the temperature dependence of the yield was detected, indicating that the mobility of the charge carriers is unaffected by these irradiations. The 1.4-ev shallow trap previously observed was split into two levels by the neutron bombardment. This supports the association of this level with the 2.2-ev optical transition. Optical absorption measurements were conducted in the 0.6- to 3.0-ev range, and a previously unreported peak has been observed at 0.74 ev.

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SUPERCONDUCTIVITY OF DILUTE INDIUM-MERCURY ALLOYS. Morton D. Reeber, International Business Machines Corporation, Research Laboratory, Poughkeepsie, New York (Received October 12, 1959).

Measurements were made of the critical magnetic field for the transition from the superconducting to the normal state in polycrystalline rods of the substitutional solid solution In-Hg, containing 0-7 atomic percent Hg. The treatment given these alloys was designed to assure homogeneity in composition in which case the transitions to the normal state were found to be similar to those for pure elemental superconductors. It was, moreover, possible to distinguish between properties that are characteristic of the ideal alloy system and properties which arise from structure within the specimen. T_c, the transition temperature at zero field, was measured as a function of composition and was found initially to decrease (up to a concentration of 1.75 atomic percent Hg) after which it began to increase with added Hg concentration. The width of the transition to the normal state, as measured by the variation of specimen resistance in a longitudinal magnetic field, was found to show a regular dependence upon composition, and also reached a minimum value at 1.75 atomic percent Hg. The superconducting properties of pure indium were measured and used as a standard. For indium it was found that $T_c = 3.407 \pm 0.002$°K, $H_c = 293$ oersteds $\pm 2\%$, and $dH_c/dT|_{T_c} = -155.5$ oersteds/°K $\pm 3\%$.

FERROELECTRIC TRANSITION IN RUBIDIUM BISULFATE. R. Pepinsky and K. Vedam, Crystal Research Laboratory, Department of Physics, The Pennsylvania State University, University Park, Pennsylvania (Received October 12, 1959).

$RbHSO_4$ is ferroelectric below -15°C. The room-temperature phase is monoclinic, with space group $P2_1/c$, $a = 14.35_8$ A, $b = 4.62_2$ A, $c = 14.80_7$ A, $\beta = 121.0°$, and $Z = 8$. The symmetry of the ferroelectric phase is Pc, as established by systematic x-ray absences and the fact that spontaneous polarization appears along the c axis below -15°C. Both the high- and low-temperature phases are pseudo-orthorhombic. The dielectric constant ϵ_c at 10 kc/sec and for a field of 5 v/cm is 10 at room temperature; as the temperature is lowered, ϵ_c rises to a sharp peak of ~240 at -15°C and falls to ~5 at -196°C. The transition appears to be of second order. No second transition, as in the case of isomorphous NH_4HSO_4, could be detected in the temperature range -15°C to -196°C.

MECHANISM FOR THE SIDEWISE MOTION OF 180° DOMAIN WALLS IN BARIUM TITANATE. Robert C. Miller and Gabriel Weinreich, Bell Telephone Laboratories, Murray Hill, New Jersey (Received October 8, 1959).

An important unanswered question concerning the sidewise motion of 180° domain walls in single-crystal $BaTiO_3$ is the mechanism by which the boundaries move. This paper considers two possible models. One model assumes that the wall motion results from the repeated nucleation of steps along existing parent 180° domain walls and that the nucleation rate is the

controlling factor in the propagation of the wall. The second model investigated involves paired screw dislocations of opposite sense which propagate the wall in a manner analogous to certain types of crystal growth.

Many features of the experimental data are consistent with the nucleation model. The nucleated steps are assumed to be triangular slabs along the wall and about one lattice constant thick. For a field of 300 v cm^{-1}, the critical nucleus is calculated to be 7×10^{-6} cm wide (along the electroded crystal surface) and 16×10^{-6} cm high (along the ferroelectric axis). For limited ranges of field, the model gives a wall velocity dependence on field of $v\propto\exp(-\delta/E)$, which agrees with experiment. The magnitude of the calculated activation field δ agrees with experiment if the energy of the additional wall consequent on a nucleation is set equal to 0.4 erg cm^{-2}. The calculated temperature dependence of δ is through $P_S{}^3T^{-1}\epsilon_a{}^{-1/2}$ and is in fair quantitative agreement with experiment. The approximately square domains observed in the low-field region are consistent with the model, and the change in shape of the domains observed at higher fields can likewise be explained if slightly different wall energies are assumed for the edges of the nucleated steps on the two different types of 180° domain walls.

The screw dislocation model does not predict a wall velocity $v\propto\exp(-\delta/E)$ in a straightforward way. It is only with certain unrealistic restrictions on the dislocation density or the wall mobility that this model will give the correct form of v. However, it is suggested that this mechanism may contribute to the wall motion with fields of a few thousand volts per centimeter or higher.

NERNST AND ETTINGSHAUSEN EFFECTS IN SILICON BETWEEN 300°K AND 800°K. Herbert Mette, Wolfgang W. Gärtner, and Claire Loscoe, U. S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey (Received October 13, 1959).

The Nernst and Ettingshausen coefficients in p-type silicon single crystals of various impurity densities have been measured over a temperature range between 300°K and 800°K at magnetic fields of 9000 gauss. The results are in good agreement with the theoretical predictions. Using the measured coefficients in the Bridgman relation, values were obtained for the thermal conductivity of silicon in the temperature range between 550°K and 800°K.

STATISTICAL POTENTIAL FOR ACTINIDE METAL ENERGY BAND CALCULATIONS. Guy W. Lehman, Atomics International, Canoga Park, California (Received October 9, 1959).

A simple analytic potential energy function, V, is developed from a Thomas-Fermi ion model for the actinide metals and is found to provide good agreement with wave functions derived from the Hartree self-consistent field approach by Ridley for the 5f, 6d, and 7s states of uranium. The estimated 5f, 6d, and 7s bandwidths are 1.1, 7.3, and 11.8 ev, respectively, in satisfactory agreement with those of Ridley.

Dirac's equations are solved for the 5f, 6d, and 7s states using this nonrelativistic potential energy function with the Wigner-Seitz boundary condition. The relativistic energy shift for the 7s state is roughly 13 ev. The $5f:5f_{7/2}:5f_{5/2}$ and $6d:6d_{5/2}:6d_{3/2}$ level separations are 0.54:0.95 and 0.68:0.80 ev, respectively.

TEMPERATURE DEPENDENCE OF THE INFRARED REFLECTION SPECTRUM OF SODIUM CHLORIDE. Marvin Hass, U. S. Naval Research Laboratory, Washington, D. C. (Received October 5, 1959).

Experimental studies of the reflection spectrum of NaCl from 300°K to 985°K were carried out in the region of the fundamental lattice absorption. This reflection spectrum was analyzed using a simple dispersion formula. The damping constant deduced in this manner varied approximately with the square of the temperature. The relation of these results to various theories of lattice absorption in solids is discussed.

PHOTOVOLTAIC EFFECTS IN CdS CRYSTALS. Hartmut Kallmann, Bernard Kramer,* Julius Shain, and Grace Marmor Spruch, Department of Physics, New York University, Washington Square, New York, New York (Received October 6, 1959).

Photovoltages were obtained in CdS crystals using inhomogeneous excitation; that is, the excitation at one electrode was much larger than

at the other electrode. Voltages in the range of 200 millivolts were obtained, with the region of high excitation always becoming positive.

Two types of electrode arrangements were used. Some crystals were contacted directly with electrodes; others were insulated from the electrodes by thin Mylar sheets. In the first arrangement the photovoltages were permanent; in the second, transient.

The photovoltage showed only a weak dependence on intensity, and only wavelengths near or shorter than that corresponding to the absorption edge were effective. With metal electrodes the photovoltages were small. However, with jelly electrodes contacting the crystals photovoltages were almost as large as for the insulated crystals.

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DIRECT CATION-CATION INTERACTIONS IN SEVERAL OXIDES. John B. Goodenough, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts (Received September 29, 1959; revised manuscript received December 14, 1959).

It is pointed out that interactions between octahedral-site cations are cation-anion-cation interactions if the cation-occupied octahedra share a common corner, but may be primarily cation-cation (no anion intermediary) if the cation-occupied octahedra share either a common edge or a common face. It is further pointed out that cation-cation interactions may be naturally classified as "strong" or "weak" since there is a critical cation separation below which the interacting electrons are best described by a collective electron model, above which by a Heitler-London model. The characteristics of the different interactions under varying conditions are summarized. In the case of strong cation-cation interactions, covalent-type bonds may be formed at low temperatures. The resulting phase transitions are marked by the following features: (1) The transitions may be noncooperative (isolated cation-cation pairing introducing no symmetry change to the structure) and extend over a considerable temperature interval ($\Delta T \sim 100°C$), or cooperative, occurring at a definite temperature and exhibiting thermal hysteresis. (2) Bonded cations are displaced from the center of symmetry of their anion interstice (in contrast to Jahn-Teller or spin-orbit distortions). (3) Bonding electrons are spin-paired so that they make no contribution to the atomic moment unless localized, unpaired d electrons are simultaneously present to weaken the covalent-type bond via intra-atomic exchange. (4) Bonding electrons cannot contribute to metallic-type conductivity so that if the bond-forming phase ties up all of the outer d electrons in covalent-type bonds, the transition is semiconducting $\rightleftarrows$ metallic. The physical properties of several compounds that illustrate the importance of the cation-cation interactions are discussed.

POLARIZED EDGE EMISSION OF SiC. W. J. Choyke, D. R. Hamilton, and Lyle Patrick, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania (Received September 21, 1959).

The photoluminescence of some relatively pure hexagonal SiC crystals (polytype 6H) includes a strongly polarized edge emission. Two distinct patterns of edge emission lines have been found, but never in the same crystal. In either type, the edge emission includes several narrow lines (half-width $\sim kT/4$ at 77°K) and a number of wider bands spaced at regular energy intervals of 0.03 ev, suggestive of a vibrational interaction. Some lines, found in the 77°K edge emission spectrum, vanish at 4°K. Mechanisms for producing polarized light are discussed, and it is concluded that the most probable luminescence centers are donor-acceptor pairs. The two types of spectra may be attributed to two different pairs. Intrinsic recombination radiation was looked for but not found.

POLARIZATION OF THE LUMINESCENCE OF DONOR-ACCEPTOR PAIRS. Lyle Patrick, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania (Received September 21, 1959).

The polarization is calculated for donor-acceptor pair luminescence in SiC. Certain degrees of polarization depend only on the axial directions of the donor-acceptor pairs, thus permitting one to identify emission by such centers in SiC, or in other uniaxial crystals with tetrahedral bonds. A comparison with experiment is inconclusive because of insufficient resolution. The Prener-Williams conclusions about nearest-neighbor donor-acceptor pairs are discussed.

INFRARED PROPERTIES OF GOLD IN GERMANIUM. L. Johnson* and H. Levinstein, Department of Physics, Syracuse University, Syracuse, New York (Received September 18, 1959).

The fundamental parameters of gold in germanium have been investigated between 60 and 300°K by absorption, photoconductivity, and lifetime studies.

Photoconductivity measurements reveal the following capture cross sections for electrons and holes at 80°K (subscript refers to carrier being captured; superscript to charge state of gold center): $\sigma_h^- \simeq 1\times10^{-13}$ cm^2, $\sigma_e^0 \simeq 6\times10^{-14}$ cm^2, $\sigma_e^- \simeq 10^{-17}$ cm^2. Lifetime studies on n-type samples show the existence of a 0.018-ev Coulomb barrier at singly-charged sites and an indication that a thermal (phonon) mechanism is involved in the electron capture process. The lifetime also manifests itself in the noise spectrum.

The photoconductive absorption cross section at 80°K of p-type gold-doped germanium (0.15-ev level) is found to be 2×10^{-16} cm^2 at 1.8 microns. It is suggested that differences between the absorption and photoconductive spectra are due to departure from spherical symmetry of valence band contours away from $k=0$.

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PIEZORESISTIVITY IN THE OXIDE SEMICONDUCTOR RUTILE (TiO_2). Lewis E. Hollander, Jr., T. J. Diesel,* and Gerald L. Vick, Lockheed Aircraft Corporation, Sunnyvale, California (Received September 11, 1959).

The piezoresistive effect in single crystals of the oxide semiconductor rutile (TiO_2) has been studied. The fourth rank piezoresistive tensor for the D_{4h} tetragonal symmetry of rutile may be expressed in terms of seven piezoresistive coefficients. Room temperature values for these coefficients are presented for different resistivity material in the range from approximately 1000 to 0.1 ohm cm, resulting from various concentrations of oxygen deficiency in the nonstoichiometric TiO_2 lattice. Some of these coefficients were also measured at 77° and 380°K. The measured piezoresistive coefficients are of the order of $+10^{-11}$ cm^2/dyne. The longitudinal piezoresistive coefficient measured along the c axis, π_{33}, diminishes with increasing oxygen deficiency, while that along the a axis, π_{11}, increases with oxygen deficiency. This trend is interpreted in terms of the impurity band conduction model proposed for rutile.

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ELASTIC SCATTERING OF NITROGEN BY CARBON. M. L. Halbert, C. E. Hunting, and A. Zucker, Oak Ridge National Laboratory, Oak Ridge, Tennessee (Received October 5, 1959).

The differential cross section for the elastic scattering of nitrogen from thin carbon foils was measured from about 40 to about 140 degrees in the center-of-mass system. The measurements were made at three energies: 27.3 Mev, 23.5 Mev, and 21.5 Mev, mean energy in the 1-Mev thick targets. The angular resolution was about 1 degree. Scattered nitrogen and recoil carbon atoms were counted in coincidence. Positions of the two counters, as prescribed by the kinematics of elastic scattering, served to discriminate against inelastic events and transfer reactions. The differential cross sections at all three energies exhibit marked structure, especially beyond 90 degrees. An optical-model scattering calculation using a Saxon potential with $V=45$ Mev, $W=6$ Mev, and $a=0.65\times10^{-13}$ cm was performed. The results of this calculation exhibit fair agreement with the data. The results of the experiment are also compared with the predictions of a sharp-cutoff model for elastic scattering and show no agreement with the theory. Analyzing the data in terms of a diffraction model, the positions of the well-defined minima yield an interaction distance R such that $r_0=(1.18\pm0.2)\times10^{-13}$ cm in the relation $R=r_0(A_1^{1/3}+A_2^{1/3})$.

HYPERFINE STRUCTURE OF F^{19} IN THE ELECTRON PARAMAGNETIC RESONANCE OF Mn:ZnF_2. A. M. Clogston, J. P. Gordon, V. Jaccarino, M. Peter, and L. R. Walker, Bell Telephone Laboratories, Murray Hill, New Jersey (Received September 17, 1959).

An experimental and theoretical re-examination of the F^{19} "super-hyperfine structure" in the electron paramagnetic resonance of Mn^{++} as a dilute, substitutional impurity in ZnF_2 has been made. The observation of anomalous spectra at 23 kMc/sec has necessitated a modification of

the phenomenological theory first offered by Tinkham. Precise measurement of all the hyperfine structure interaction constants, in conjunction with the new theory, allows direct comparison to be made with the results of the nuclear magnetic resonance experiments of F^{19} in MnF_2. The agreement now found is most satisfactory. The theory of the origin of the F^{19} hyperfine structure is discussed in the light of recent work of Mukherji and Das, Marshall, and Keffer et al.

The Mn^{55} hyperfine structure was measured and found to be anisotropic. This, in conjunction with Mn^{55} specific heat measurements in antiferromagnetic MnF_2, enables one to compute the magnetization of a sublattice at $T = 0°K$.

DETERMINATION OF THE SURFACE TENSION AND SURFACE MIGRATION CONSTANTS FOR TUNGSTEN. J. P. Barbour, F. M. Charbonnier, W. W. Dolan, W. P. Dyke, E. E. Martin, and J. K. Trolan, Linfield Research Institute, McMinnville, Oregon (Received October 1, 1959).

A determination of the surface tension and surface migration constants of metals in the solid phase, based on the use of pulsed field emission microscopy, is discussed. The experimental technique is described. An application to field emission cathodes of Herring's theory of transport phenomena in solids is given, which yields the necessary relations required for the determination of the basic physical constants from the experimental data. Results are presented and discussed for the case of tungsten. The method is applicable to a number of other metals, several of which are currently under investigation.

H_1^- PRODUCTION BY HYDROGEN POSITIVE-ION BOMBARDMENT OF A TUNGSTEN SURFACE. L. P. Levine* and H. W. Berry, Department of Physics, Syracuse University, Syracuse, New York (Received October 2, 1959).

An experimental and theoretical study of the energy distribution of the negative ions is described. The double mass spectrograph used allows analysis of both the incoming positive- and outgoing negative-ion beams. Two peaks are studied: a low-energy peak of negative hydrogen ions created by the bombardment of a dirty surface by an assortment of positive ions, and a high-energy peak of negative hydrogen ions created only under bombardment of a surface by H_2^+ and H_1^+. The height of the low-energy peak is found to be proportional to the amount of hydrogen on the surface. The curve has a peak three electron volts wide at its half-maximum, and a tail 25 electron volts long on the high self-energy side. The high-energy peak ranges from zero self-energy to a value resulting from a head-on collision between a proton in the incoming ion beam and one of the atoms in the surface. This curve is flat over its entire energy range, dropping to zero at the low self-energy end independent of incident-ion energy. On a clean surface the shape of this curve is independent of target temperature.

The shape of the high-energy curve is compared with curves predicted by a random walk-collision theory and a theory based on the loss and gain, due to scattering, of particles in velocity groups. The shape of the low-energy curve is compared with curves predicted by a theory of thermal desorption of ions from a surface coupled with a mechanism for neutralization of ions as they leave the surface

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HYPERFINE SPLITTING OF THE LITHIUM GROUND STATE. Lester M. Sachs, Argonne National Laboratory, Lemont, Illinois, and Illinois Institute of Technology, Chicago, Illinois (Received October 12, 1959).

The results of calculations of the hyperfine splitting of the lithium atom ground state are reported. These were done by the Hartree-Fock (HF), unrestricted Hartree-Fock (UHF) and projected UHF approximations to the ground-state eigenfunctions. The exchange polarization effect allowed by the UHF method yields a 34.9% increase in the hyperfine splitting compared to that obtained by the HF method.

HARTREE-FOCK EQUATIONS WITH A PERTURBING FIELD. Leland C. Allen, Department of Physics, University of California, Berkeley, California (Received October 19, 1959).

The Hartree-Fock equations under the action of an arbitrary field for any order of perturbation are set up in an integro-differential form. This form appears particularly advantageous

for practical computation in such problems as electronic polarizability and electronic structure perturbations caused by nuclear moments. The equations are explicitly written down for a uniform perturbing field and a comparison is made with previous formulations. A wide variety of other applications are also discussed.

UPPER BOUNDS ON SCATTERING LENGTHS WHEN COMPOSITE BOUND STATES EXIST. Leonard Rosenberg, Larry Spruch, and Thomas F. O'Malley, Physics Department, Washington Square College and Institute of Mathematical Sciences, New York University, New York, New York (Received October 19, 1959).

In the case of the zero-energy scattering of one compound system by another, where one real scattering length completely characterizes the problem, (e.g., the reaction $A+B\rightarrow C+D$, in addition to $A+B\rightarrow A+B$, cannot take place) it has previously been shown that the Kohn-Hulthén variational principle provides an upper bound on the scattering length if no composite bound states exist. The extension of this result to the case where one or more composite bound states do exist is presented here. The inclusion of tensor forces, exchange forces, and Coulomb forces is allowed. Several methods are given for obtaining a rigorous upper bound on the scattering length, which involve the addition of certain positive terms to the Kohn-Hulthén variational expression. The approximate information about the composite bound states which is required to construct these additional terms can be found by standard methods. As a consequence of one of the results obtained, it is shown that under certain circumstances some ordinary variational calculations give a bound. Thus, an analysis of a previous calculation in the light of the present results leads, without further calculations, to a rigorous upper bound on the singlet electron-hydrogen scattering length.

ISOMERISM OF SILVER-108. Morris A. Wahlgren and W. Wayne Meinke, Department of Chemistry, University of Michigan, Ann Arbor, Michigan (Received October 5, 1959).

A long-lived isomer of Ag^{108} has been detected in old Ag^{110m} samples. The isomer decays with a half-life $\geqslant 5$ years. Gamma- and beta-ray spectrometer data show that 90% of the disintegrations proceed by electron capture followed by a cascade of three gamma rays of 616-, 722-, and 434-kev energy, while 10% go by isomeric transition to Ag^{108}. New values are given for the branching ratios of 2.4-minute Ag^{108}.

ACTIVATION CROSS SECTIONS FOR 14.8-MEV NEUTRONS AND SOME NEW RADIOACTIVE NUCLIDES IN THE RARE EARTH REGION. R. G. Wille and R. W. Fink,* Department of Chemistry, University of Arkansas, Fayetteville, Arkansas (Received September 21, 1959).

Activation cross sections on 27 stable nuclides of elements Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Er, Yb, and Lu were measured for 14.8 ± 0.8 Mev neutrons. Highly enriched isotopes were used as targets in most cases, and in a few instances radiochemical separations were performed whenever it was necessary and possible in view of the product half-lives. The measured cross sections for $(n,2n)$ reactions were found to agree within an order of magnitude with predictions from statistical evaporation theory. However, experimental values of (n,p) and (n,α) cross sections generally appear to be larger than calculated from continuum theory of the compound nucleus. The cross sections show no significant effects due to the 82-neutron closed shell and, furthermore, the Levkovskii effect, which is quite striking in the low-Z region, appears to be negligible for (n,p) and (n,α) reactions in the rare earth region. The $(n,2n)$ cross sections show little variation with mass number at constant Z, and they exhibit a decrease with increasing mass number at $N=82$.

Several previously unreported activities were observed; their half-lives, assignments, and gamma radiations are as follows: 12 ± 3 min Pr^{148} from the $Nd^{148}(n,p)$ reaction; 0.5 ± 0.1 min Sm^{157} from the $Gd^{160}(n,\alpha)$ reaction, 0.57 ± 0.01 Mev γ ray; 7 ± 1 min Tb^{163} from the $Dy^{163}(n,p)$ reaction, 0.18 ± 0.05 Mev γ ray; 3.3 ± 0.5 min Ho^{168} from the $Er^{168}(n,p)$ reaction, 0.85 ± 0.05 Mev γ ray; 40 ± 10 sec Ho^{170} from the $Er^{170}(n,p)$ reaction; 4.4 ± 0.4 min Dy^{167} from the $Er^{170}(n,\alpha)$ reaction; 2.0 ± 0.5 min activity with gammas at 0.18 ± 0.01, 0.25 ± 0.01, and 0.36 ± 0.01 Mev which may be Tm^{176}, Er^{173}, or possibly isomeric Yb^{177m} from enriched Yb^{176} bombardments. Tentative assignment of a 5.5 ± 0.5 min activity to Tm^{174} is sug-

gested from bombardment of enriched Yb^{174}.

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ANALYSIS OF ELASTIC CROSS SECTIONS AND POLARIZATION OF 10-Mev PROTONS. J. S. Nodvik, University of Southern California, Los Angeles, California, and David S. Saxon, University of California, Los Angeles, California (Received October 6, 1959).

The differential elastic cross section and polarization of 10-Mev protons scattered by argon and copper have been analyzed using a diffuse-surface optical model potential with a spin-orbit term. The model parameters were varied systematically, the best fits with the experimental data being determined by a method of least squares. As in other analyses, it was found that almost equally good fits could be obtained over a range of values of the radius constant, R_0, in this case for R_0 approximately between 1.20 and 1.30. Only the value of the real part of the central potential was markedly different for the best fits obtained for various R_0 in this range. The experimental polarization data are not precise enough to determine the spin-orbit potentials to within better than 1 or 2 Mev.

PHOTODISINTEGRATION OF Li^6. D. G. Proctor* and W. H. Voelker, Case Institute of Technology, Cleveland, Ohio (Received October 26, 1959).

The photodisintegration of Li^6 by bremsstrahlung radiation of 17.3-Mev peak energy was investigated by use of coincidence techniques to detect neutron-proton coincidence and by measurement of the photoproton energy spectra. The $Li^6(\gamma,n)Li^5$ reaction is found to be responsible for 0.58 ± 0.13 of the photoneutron yield measured by Romanowski while the $Li^6(\gamma,p)He^5$ reaction contributes 0.31 ± 0.04 of the yield. No angularly correlated neutron-proton coincidences were detected which would support a deuteron–alpha-particle model for the $Li^6(\gamma,np)He^4$ reaction; however, the possible existence of this reaction is not eliminated.

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SPIN STATES ASSOCIATED WITH NEUTRON RESONANCES IN In^{115}. A. Stolovy, U. S. Naval Research Laboratory, Radiation Division, Washington, D. C. (Received October 19, 1959).

By polarizing both the neutron beam and the nuclear sample, the spin states of the first three slow-neutron resonances in the target nucleus In^{115} have been measured. These were obtained by observing the direction of change in the transmitted intensity upon reversing the polarization of the neutrons with respect to the target nuclei. The spin states associated with the resonances at 1.46 ev, 3.86 ev, and 9.10 ev were found to be $J = 5$, 4, and 5, respectively. These spin assignments are consistent with measurements of other parameters of these resonances.

THE ISOTOPES Np^{240} AND Np^{241}. Richard M. Lessler,* and Maynard C. Michel, University of California, Lawrence Radiation Laboratory, Berkeley, California (Received October 27, 1959).

The 1-hour neptunium activity which had previously been assigned to Np^{241} has been identified as the lower isomer of Np^{240}. The decay energy of the 1-hour Np^{240} has been found to be 2.05 Mev compared with 2.156 Mev for that of the 7.3-min Np^{240}. Gamma rays of energies 1160, 1000, 915, 595, 565, 435, 245, 160, and 85 kev have been found to be associated with the decay of Np^{240}. The best value for the half-life of Np^{240} is 63 ± 2 min. The isotope Np^{241} has been found to have a 16-min half-life with strong evidence for an isomer with a 3.4-hour half-life.

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NUCLEAR PAIR EMISSION FROM THE 7.656-Mev LEVEL IN C^{12}. David E. Alburger,* Oak Ridge National Laboratory, Oak Ridge, Tennessee, and Brookhaven National Laboratory, Upton, New York (Received October 29, 1959).

The 7.656-Mev nuclear pair transition from the 0+ second excited state of C^{12} has been observed in the $Be^9(\alpha,n)C^{12}$ reaction by means of an intermediate-image pair spectrometer. With a beam of 5.81-Mev alpha particles incident on a 0.7-Mev thick Be foil target, the observed intensity

ratio of the 7.656-Mev pair line to the 4.433-Mev pair line from the 2+ first excited state of C^{12} was $(5 \pm 1.5) \times 10^{-4}$. Approximately the same intensity ratio was found with both 5.38- and 5.81-Mev alpha particles incident on thick (6 mg/cm^2) Be targets. By applying the appropriate factors for the spectrometer efficiency and for the internal pair conversion coefficient of the 4.433-Mev transition, the derived ratio of pair to total widths of the 7.656-Mev level is $\Gamma_{e\pm}/\Gamma = 8.2 \times 10^{-7} \times R$, where $R = N_{4.433}/N_{7.656}$, the ratio of neutron populations in the $Be^9(\alpha, n)C^{12}$ reaction. As a rough estimate R is assumed to be ~8 based on the only information available. This leads to $\Gamma_{e\pm}/\Gamma \sim 7 \times 10^{-6}$ which is a factor of ~15 smaller than estimates by Cook et al. in which the width Γ_α for the alpha-particle decay of the level was taken as 1/10 of the Wigner limit. The most plausible explanation of the data is that Γ_α is close to the Wigner limit.

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NUCLEAR SPIN OF SAMARIUM-153. Amado Cabezas, Edgar Lipworth, Richard Marrus, and Joseph Winocur, Department of Physics and Lawrence Radiation Laboratory, University of California, Berkeley, California (Received October 28, 1959).

The atomic-beam magnetic-resonance method has been used to measure the nuclear angular momentum of 47-hour Sm^{153}. It is found that $I = 3/2$.

THEORY OF THE PHOTODISINTEGRATION OF THE DEUTERON. L. D. Pearlstein* and A. Klein, University of Pennsylvania, Philadelphia, Pennsylvania (Received August 31, 1959).

By means of a covariant field-theoretic technique, a formally exact expression has been derived for the amplitude for photodisintegration of the deuteron. By expanding the result only in the number of mesons exchanged and by making a series of nonrelativistic approximations, the expression is reduced to one in which the corrections to the conventional dipole matrix element depend only on the amplitude for photomeson production, the renormalized meson-nucleon coupling constant, and the appropriate two-nucleon wave functions. One finds that virtual meson effects play little role at energies below 100 Mev, in justification of recent calculations based on the conventional nonrelativistic theory. At higher energies good agreement with the total cross section was obtained by the inclusion of both hard-core and tensor-force effects in the wave functions. In addition the folded angular distribution could be fitted by using a reasonable extrapolation of the phase shifts in the $^1S_0$ and $^1D_2$ states.

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PROPERTIES OF THE EXCITED STATES OF Na^{22} FROM THE $Ne^{21}(p, \gamma)$ REACTION. R. W. Krone and J. J. Singh, Department of Physics, University of Kansas, Lawrence, Kansas (Received July 8, 1959; revised manuscript received November 13, 1960).

Proton capture resonances in Ne^{21} have been observed at 775 kev, 865 kev, 1010 kev, 1120 kev, 1215 kev, 1296 kev, and 1354 kev for proton bombarding energies ranging between 600 kev and 1500 kev. Pulse-height spectra of the resultant gamma radiation are presented for the two lowest resonances. At the 776-kev resonance the transitions are predominantly to the ground state, whereas the 865-kev resonance seems to decay mainly to the 2.25-Mev state. Arguments are presented showing that this is consistent with identifying this level as the second $T = 1$, $J = 2^+$ state in Na^{22}.

ELASTIC SCATTERING OF ALPHA PARTICLES BY O^{16}. L. C. McDermott, K. W. Jones,* H. Smotrich, and R. E. Benenson,† Columbia University, New York, New York (Received October 19, 1959).

Absolute cross sections for the elastic scattering of alpha particles by O^{16} have been measured in a differentially pumped gas scattering chamber. The measurements were made for laboratory energies from 3.7 to 6.5 Mev, corresponding to 7.7- to 9.9-Mev excitation in Ne^{20}, at center-of-mass angles of 168.9°, 149.4°, 140.8°, 125.3°, and 90.0°.

Narrow resonances were observed at bombarding energies of 5.002, 5.11, 5.190, 5.432, 5.532, and 6.030 Mev. The data were analyzed in terms of Wigner-Eisenbud dispersion theory

to find the spins, parities, resonance energies, widths, reduced widths, and characteristic energies of the levels. The resonances observed correspond to states in Ne^{20} with the following excitation energies, spins, and parities: 8.755 (1^-), 8.84 (5^-), 8.905 (1^-), 9.099 (4^+), 9.179 (3^-), and 9.577 Mev (2^+). In order to obtain a good fit to the data it was necessary to assume the existence of two broad overlapping resonances, one at ~8.7-Mev excitation (0^+) and the other at ~8.8 Mev (2^+). There is also some evidence for the presence of a broad 4^+ level at an energy higher than 9.9-Mev excitation in Ne^{20}.

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REACTIONS OF PROTONS WITH Ni^{58} AND Ni^{60}. Sheldon Kaufman, Frick Chemical Laboratories, Princeton University, Princeton, New Jersey (Received October 9, 1959).

Excitation functions up to 19 Mev have been measured for the $Ni^{58}(p,2p)$, $Ni^{58}(p,pn)$, and $Ni^{58}(p,\alpha)$ reactions, and for the $Ni^{60}(p,\alpha)$ reaction up to 13 Mev. The ratio of the $(p,2p)$ cross section to the (p,pn) cross section is 3.5 at 19 Mev, and increases with decreasing energy. It is proposed that this excess of proton emission can be accounted for by nuclear evaporation theory, and a computer calculation of the excitation functions using this theory is described. The calculation reproduces the $(p,2p)$ and (p,pn) curves quite well, and gives evidence that the compound nucleus mechanism probably applies to these reactions. The calculated (p,α) curve does not agree with the experimental results as well.

SINGLE-PARTICLE MOTION IN A DEFORMED, NONLOCAL POTENTIAL WELL. R. H. Lemmer, Department of Physics, Florida State University, Tallahassee, Florida (Received October 2, 1959).

The effects of the nonlocal character of the average nucleon-nucleus interaction on single-particle motion in a strongly deformed field are examined by using a simple phenomenological description of the nonlocal interaction and introducing an effective-mass approximation for a finite nuclear system.

The eigenvalues and eigenfunctions of the anisotropic harmonic oscillator potential are used as a starting point for a perturbative treatment of the nonlocal interaction, and the resulting energy level scheme is given as a function of the nuclear deformation. A conventional spin-orbit interaction has also been included in these calculations.

The main effects of the nonlocal interaction appear as an increase in the level spacing of the unperturbed oscillator states combined with an additional interaction energy which can be interpreted as an effective angular momentum dependence of the average potential field.

Calculations of nuclear equilibrium deformations based on the computed level schemes are presented. It is found that the preponderance of prolate nuclear shapes found empirically can be accounted for quite well by the nonlocal model and results essentially from the favoring of high angular momentum substates that is introduced by the nonlocal interaction.

F^{19}, Na^{23}, AND Al^{27} (α,n) REACTIONS. R. M. Williamson, T. Katman, and B. S. Burton,* Duke University, Durham, North Carolina (Received September 28, 1959).

The F^{19}, Na^{23}, and Al^{27} (α,n) yield curves are given from threshold to about 4 Mev. Convenient resonances for alpha-particle energy calibration in these reactions and in the $C^{13}(\alpha,n)$ reaction are pointed out. "Slow-fast" neutron data and γ-ray data for $F^{19}(\alpha,n)$ agree with the proposed 593- and 666-kev Na^{22} levels. The Al^{26m} (228 kev) β activity was observed in the $Na^{23}(\alpha,n)$ reaction. The neutron resonance absorption technique gave $Q = -1959 \pm 10$ kev for $F^{19}(\alpha,n)$. The $32° \pm 3°$ angle cutoff of $Na^{23}(\alpha,n)$ neutrons at $T_\alpha = 3492 \pm 3$ kev gave a Q value of -2969 ± 4 kev. The threshold for P^{30} β activity gave $Q \geq -2662 \pm 5$ kev for $Al^{27}(\alpha,n)$.

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RADIOACTIVE DECAY OF Lu^{168}. R. G. Wilson and M. L. Pool, Department of Physics and Astronomy, Ohio State University, Columbus, Ohio (Received October 26, 1959).

Ytterbium oxide enriched to 30.9% in the 168 mass number was irradiated with 6-Mev protons. An activity decaying by electron capture with a half-life of 7.1 ± 0.2 minutes was produced and assigned to Lu^{168}. The activity consists of

gamma rays with energies of 87±1, 900±7, 987±7, 1410±20, 1800±40, 2130±60 kev in addition to the ytterbium K x ray. An energy level scheme for this decay is presented.

NEW NEUTRON-DEFICIENT ISOTOPES OF TANTALUM. K. T. Faler* and J. O. Rasmussen, Lawrence Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California (Received April 15, 1959).

Bombardment of Ho_2O_3 with N^{14} ions in the Berkeley heavy-ion linear accelerator has resulted in the discovery of two new isotopes of tantalum which have been assigned as Ta^{173} and Ta^{174}. They have half-lives of 3.7 hr and 1.3 hr, respectively. Tantalum-172 was not observed and is believed to have a half-life shorter than 30 minutes. Gamma-ray spectra have been obtained for these two isotopes and for Ta^{175}. Tantalum-175, with an 11-hr half-life, has also been produced by 48-Mev alpha-particle bombardment of Lu_2O_3, and its conversion-electron spectrum was studied. From these data a decay scheme is proposed using nine of the observed transitions and assigning spins to three members of the ground-state rotational band.

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ENERGY LEVELS IN Ne^{20} FROM THE $F^{19}(d, n\gamma)Ne^{20}$ REACTION. J. W. Butler, Nucleonics Division, U. S. Naval Research Laboratory, Washington, D. C. (Received October 21, 1959).

The gamma-ray threshold technique has been used with the $F^{19}(d, n\gamma)Ne^{20}$ reaction to find excited states in the residual nucleus, Ne^{20}. Thin targets of CaF_2 were bombarded with deuterons from a 2-Mev Van de Graaff accelerator. Two NaI(Tl) crystals (1.75 in. ×1.75 in. and 3 in. ×3 in.) were used in a coincidence arrangement to measure the gamma rays as a function of deuteron energy. Nine gamma-ray or neutron thresholds were found, at bombarding energies of 0.51±0.02, 0.60±0.02?, 0.76±0.02, 0.85 ±0.02?, 1.15±0.02, 1.35±0.02, 1.70±0.02, 1.79±0.02, and 2.06±0.02 Mev. These threshold energies correspond to excited states in Ne^{20} at 11.11±0.02, 11.19±0.02?, 11.33±0.02, 11.42±0.02?, 11.69±0.02, 11.87±0.02, 12.19 ±0.02, 12.27±0.02, and 12.51±0.02 Mev, respectively. All of these states decay principally to the ground state of Ne^{20} except the 11.11-, 11.19-, and 12.27-Mev states, which decay primarily to the 1.63-Mev state. Possible isobaric spin assignments are discussed.

(n, He^3) REACTIONS OF MEDIUM WEIGHT NUCLEI INDUCED BY 14.8-Mev NEUTRONS. I. Kumabe,* A. D. Poularikas, I. L. Preiss, D. G. Gardner, and R. W. Fink,† Department of Chemistry, University of Arkansas, Fayetteville, Arkansas (Received October 7, 1959).

Activation of the following pure monoisotopic elements with 14.8-Mev neutrons gives rise to (n, He^3) reactions as observed by measuring the radioactive products having the following measured half-lives and formation cross sections: $Mn^{55}(n, He^3)V^{53}$, 2±0.3 min, 2-6 mb; $Co^{59}(n, He^3)Mn^{57}$, 1.75±0.2 min, 1-3 mb; $As^{75}(n, He^3)Ga^{73}$, 5.1±0.3 hours, 3-7 mb; and $Rh^{103}(n, He^3)Tc^{101}$, 15±3 min, 1.5-3.5 mb. A qualitative discussion is presented concerning the possible mechanisms for these reactions. Work is being continued to observe other (n, He^3) reactions.

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BETA-GAMMA DIRECTIONAL CORRELATION IN THE DECAY OF Co^{60} AND Na^{22}. H. Daniel* and G. W. Eakins, Institute for Atomic Research and Department of Physics, Iowa State University, Ames, Iowa (Received October 8, 1959).

The differential and integral beta-gamma directional correlations in the decay of Co^{60} and Na^{22} have been measured with scintillation counters. Both beta transitions are allowed but have high ft values. Therefore, small anisotropies are not excluded. In the case of Co^{60} the anisotropy was found to be zero for all beta energies above 0.06 Mev; the integral anisotropy was measured to be $A = -0.0003 \pm 0.0017$ (standard deviation). In the case of Na^{22} the results seem to indicate an energy dependence of the anisotropy; the value is uncertain because of coincidences between positrons and annihilation quanta.

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EVALUATION OF THE INTERACTION EFFECT IN n-p CAPTURE. N. Austern and E. Rost, University of Pittsburgh, Pittsburgh, Pennsylvania (Received October 8, 1959).

Recent information about the nuclear force has been used to recalculate the thermal n-p capture cross section, and a value of 0.303 ± 0.012 b is obtained. The comparison of this number with the experimental cross section of 0.3315 ± 0.0017 b indicates an "interaction" magnetic dipole moment contribution of 0.028 ± 0.012 b.

HIGHER RESONANCES IN PION-NUCLEON INTERACTIONS. Ronald F. Peierls,* Lawrence Radiation Laboratory, University of California, Berkeley, California (Received October 9, 1959).

The recent experiments on pion-nucleon scattering and photoproduction at energies up to about 1.2 Bev are examined from a phenomenological standpoint. The most useful information seems to come from the photoproduction angular-distribution and polarization results. The data seem to imply the existence of two "resonances" in the $J = 3/2$, odd parity and $J = 5/2$, even parity states at photon energies of about 750 and 1100 Mev. These assignments satisfy several non-trivial consistency requirements. The same two states are also a consistent assignment for the observed scattering resonances at 615 Mev and 950 Mev. A qualitative model is proposed to explain these resonances as consequences of the 33 resonance acting in two-meson final states; their isotopic spin dependence seems to require some additional assumptions. Finally, the relation between the photoproduction and scattering phases in the presence of strong inelastic scattering, is examined.

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LOW-ENERGY PION PHENOMENA. J. Hamilton, Christ's College, Cambridge, England, and W. S. Woolcock, Clare College, Cambridge, England (Received October 22, 1959).

The relation between low-energy pion-nucleon scattering and pion photoproduction is examined. Correct extrapolation to threshold of both the π^+ and π^- photoproduction data gives agreement with theory. A recent new method for analyzing the scattering data is applied, giving $a_1 = 0.178$, $a_3 = -0.087$, and reasonable agreement with the Panofsky ratio $P = 1.5$ is obtained. An inner Coulomb correction to the scattering data helps to improve this agreement. The possibility of detecting a π-π interaction by low-energy pion scattering is examined. A new dispersion relation connects the s- and p-wave phase shifts at low energies; this relation excludes some well-known sets of phase shift curves.

SCATTERING OF HIGH-ENERGY NUCLEONS BY A NONLOCAL POTENTIAL. R. H. Lemmer and Y. C. Tang, Department of Physics, Florida State University, Tallahassee, Florida, and W. E. Frahn, Nuclear Physics Division, National Physics Laboratory, Council for Scientific Industrial Research, Pretoria, South Africa (Received October 21, 1959).

The scattering of high-energy nucleons by a simple nonlocal potential is examined in the Born approximation. It is shown that an energy-dependent local potential is not fully equivalent to a nonlocal potential. The latter potential introduces an additional angular dependence in the differential cross section which seems to be particularly significant in the backward direction.

π^--PROTON SCATTERING AT 1 Bev AND A COMPARISON WITH THE LINDENBAUM-STERNHEIMER MODEL. I. Derado and N. Schmitz, Max-Planck-Institut für Physik und Astrophysik, München, Germany (Received August 6, 1959).

In photographs from the 10-in. hydrogen bubble chamber at Berkeley we have analyzed 640 π^--proton scattering events with two secondary tracks. The primary π^- energy was 1 Bev. The cross sections for the various reactions and especially for the reactions

$$\pi^- + p \rightarrow \pi^- + p,$$

$$\pi^- + p \rightarrow \pi^- + n + \pi^+,$$

$$\pi^- + p \rightarrow \pi^- + p + \pi^0$$

have been determined. The ratio $\sigma(\pi^- + p + \pi^0)/\sigma(\pi^- + n + \pi^+)$ of the two inelastic reactions turned out to be $0.50^{+0.12}_{-0.14}$. The differential cross section of the π^- for the elastic scattering and the momentum and angular distributions of the

secondary particles from the two inelastic processes are given.

Our momentum spectra exhibit two maxima which strongly indicate the existence of the isobaric nucleon state. However, our results can hardly be explained by the Lindenbaum-Sternheimer model quantitatively, as has been shown in two independent ways. Perhaps this discrepancy is an indication that those pion productions must not be neglected which do not go through the intermediate state of the isobar but through the direct channel.

RESONANT SCATTERING OF ANTINEUTRINOS. Sheldon L. Glashow, Institute for Theoretical Physics, Copenhagen, Denmark (Received October 26, 1959).

The hypothesis of an unstable charged boson to mediate muon decay radically affects the cross section for the process $\bar{\nu}+e\rightarrow\bar{\nu}+\mu^-$ near the energy at which the intermediary may be produced. If the boson is assumed to have K-meson mass, the resonance occurs at an incident antineutrino energy of $\sim 2\times 10^{12}$ ev. The flux of energetic antineutrinos produced in association with cosmic-ray muons will then produce two muon counts per day per square meter of detector, independently of the depth and the orientation at which the experiment is performed.

DECAY RATES OF BOUND NEGATIVE MUONS. D. D. Yovanovitch, The Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois (Received September 24, 1959).

The decay rate of negative muons bound to nuclei of atomic number Z, $\Lambda_d(Z)$, has been investigated experimentally by two independent methods: (a) the "sandwich" method, and (b) the "calibrated efficiency" method. Both methods are based on the fact that the negatron yield per muon, $y^-(Z)$, is proportional to $\Lambda_d(Z)/\Lambda_t(Z)$, where $\Lambda_t(Z)$ is the total disappearance rate of negative muons for element Z, and are designed to avoid absolute measurements of $y^-(Z)$. In Method (a), μ^- are stopped in a multilayer "sandwich" target made by alternately stacking sheets of two elements Z, Z', and the resultant e^- time distribution is decomposed into components due to Z and Z'. The ratio of muon stops in Z and Z' is established empirically; knowing $\Lambda_d(Z')$, $\Lambda_d(Z)$ can be computed. This method was applied to Al, Fe, Zn, Cd, Mo, W, and Pb. In Method (b), μ^- and μ^+ of identical range distributions are stopped in a given target, and the e^+ yield, y^+, is used as a calibration of the e^- counting efficiency. This method has been applied to C, Ca, Ti, V, Mn, Fe, Co, Ni, Zn, I, and Pb. The sources of error of either method are discussed in detail. The results indicate:

(1) In the range $20<Z<30$, $\Lambda_d(Z)>\Lambda_d(0)$, i.e., the bound decay rate exceeds the vacuum (i.e., μ^+) decay rate; $\Lambda_d(Z)$ presents a sharp peak near $Z=26$.

(2) For $Z>30$, one finds $\Lambda_d(Z)<\Lambda_d(0)$, i.e., the decay is inhibited by binding. The effect is very marked for the heaviest elements, e.g., $\Lambda_d(82)/\Lambda_d(0)=0.34\pm 0.04$.

These results are compared with the predictions of simplified theoretical models. The peak near $Z=26$ is tentatively attributed to the Coulomb enhancement of the outgoing electron wave function at the point of decay.

PHOTOPRODUCTION OF NEUTRAL PIONS AT FORWARD ANGLES. Karl Berkelman and James A. Waggoner, Laboratory of Nuclear Studies, Cornell University, Ithaca, New York (Received October 12, 1959).

The bremsstrahlung beam of the Cornell Bev electron synchrotron has been used to study the reaction $\gamma+p\rightarrow\pi^0+p$ over the photon energy range 250 Mev to 1 Bev, and for center-of-mass pion angles between 20° and 70°. The recoil protons, of energies between 10 and 60 Mev, were identified and their energies determined using a range telescope of eight thin plastic scintillators enclosed in a vacuum chamber with the thin liquid hydrogen target. Correlated pulse-height information was obtained by photographing an oscilloscope display and was used to sort out the protons from mesons and electrons. Corrections were made for the background of photoprotons from the Mylar target cup, the energy loss of the protons in the liquid hydrogen, absorption and scattering in the counter telescope, and the variation of beam intensity profile with energy. Compared with previous experiments and extrapolations the results show a somewhat smaller forward differential cross section above 400 Mev. The angular distributions obtained from a least-

squares fit to all existing data indicate a $d_{3/2}$ assignment for the 760-Mev resonance level. Other implications of the data are also discussed.

MUON DECAY IN NUCLEAR EMULSION AT 25 000 GAUSS. G. R. Lynch* and J. Orear, Laboratory of Nuclear Studies, Cornell University, Ithaca, New York, and S. Rosendorff,† Department of Physics, Columbia University, New York, New York (Received September 8, 1959).

Positive pions from the 90-Mev pion beam of the Nevis cyclotron were stopped in nuclear emulsion which was in a magnetic field of 25 000 gauss. The asymmetry parameter for the angular distribution of the positrons which came from the decay muons was measured. The result that $P\xi = -0.87 \pm 0.04$ implies that either the asymmetry parameter ξ is different from the value of -1 predicted by the V-A theory or that there is about 13% depolarization of positive muons in nuclear emulsion at 25 000 gauss.

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ABSORPTION OF NEGATIVE MUONS IN C^{12} LEADING TO PRODUCTION OF BOUND B^{12}. J. G. Fetkovich, T. H. Fields, and R. L. McIlwain,* Carnegie Institute of Technology, Pittsburgh, Pennsylvania (Received September 8, 1959).

A negative muon beam from the Carnegie Institute of Technology synchrocyclotron was stopped in a six-inch propane bubble chamber. Since the hydrogen does not form μ-mesonic atoms in the presence of carbon, the pictures yield information on the interaction of stopped muons with carbon. About 30 000 pictures of stopping muons were taken with the bubble chamber kept sensitive for ~20 msec after the beam pulse in order to observe the beta decay of any bound B^{12} nuclei resulting from μ absorption by carbon. The chamber was photographed right after the beam pulse to determine whether a given stopped muon decayed, or was absorbed. Another photograph was taken about 15 msec later to determine if the absorption had led to a nucleus which had beta-decayed. A count of μ-e decays in the same film allowed the determination of the probability per unit time of bound B^{12} formation. Forty-six boron decays were observed yielding $(7.6 \pm 1.2) \times 10^3$ sec^{-1} for the rate of bound B^{12} production. Possible interpretation of this result in terms of a universal V-A Fermi interaction is discussed.

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CHARGE-EXCHANGE CROSS SECTION OF 175- TO 250-Mev K^+ IN CARBON, COPPER, TUNGSTEN, AND NUCLEAR EMULSION. Marian N. Whitehead, Robert E. Lanou, Jr., Victor Cook, Jr., and Robert W. Birge, Lawrence Radiation Laboratory, University of California, Berkeley, California (Received October 19, 1959).

The disappearance and presumed charge exchange of K^+ mesons has previously been observed in nuclear emulsions. We have measured the charge-exchange cross section for K^+ energies between 150 and 250 Mev in C, Cu, W, and, as a check, in nuclear emulsion. In addition, a scintillation-counter array was used to detect the charged decay mode of the short-lived K_1^0 produced in the charge-exchange reaction. The measured mean free path in nuclear emulsion is 195 ± 25 cm at 200 Mev. The average corrected free-neutron cross section deduced from the pure elements is 5.9 ± 0.4 mb.

From K^+ charge exchange, and assuming a branching ratio of 1/3 for decay into the $2\pi^0$ mode compared to all decays for the K_1^0 state, we find a K_1^0/K_2^0 ratio consistent with unity.

MAGNETIC QUENCHING OF HYPERFINE DEPOLARIZATION OF POSITIVE MUONS. R. A. Ferrell, Y. C. Lee, and M. K. Pal,* University of Maryland, College Park, Maryland (Received August 24, 1959).

The depolarization of positive muons being slowed down in an insulating material can only be accounted for by the capture of an electron into a bound state. The ground state muonium formed in flight can be expected to break up in a time short compared to 10^{-10} sec (the time necessary for the electron to flip the muon spin via the hyperfine interaction). The effect of an external magnetic field in locking the electron spin in its initial orientation, and thereby quenching the action of the hyperfine coupling,

is a useful test of the assumption of muonium as the depolarizing mechanism. If x is the magnetic field strength measured in units of 1.58 kilogauss, and τ is twice the mean life of the muonium atoms with respect to breakup, measured in units of 3.58×10^{-11} sec, then it is found that the amount of depolarization for one formation and breakup process is equal to one-half of the quantity $(1+\tau^{-2}+x^2)^{-1}$. By introducing n, the number of times that the capture-breakup process is repeated, one has two parameters and can achieve good fits to the experimental data of Sens et al. for nuclear emulsion and fused quartz. It is pointed out that the interpretation by Sens et al. of their magnetic quenching data, also based on a two-parameter formula, is not tenable, since it depends on assuming that a certain fraction of the muons are not subject to the capture and loss process.

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ENERGY DEPENDENCE OF TRANSIENT CHANGES IN THE PRIMARY COSMIC-RAY SPECTRUM. K. G. McCracken, Physics Department, University of Tasmania, Hobart, Tasmania (Received June 12, 1959).

Quantitative comparisons are made between the cosmic-ray intensity variations observed by a Geiger counter telescope and ionization chamber at a high geomagnetic latitude, high-latitude neutron monitors at sea level, and at two different mountain altitudes, Geiger counter telescopes situated 40 meters of water equivalent underground, and a neutron monitor and Geiger counter telescopes at a low geomagnetic latitude. Long-term, and short-term variations are considered. As the intensity variations were large, and as the instruments were all of good statistical accuracy, considerable reliance can be placed in the determinations. It is shown that similar comparisons published by other investigators are in agreement with these determinations, provided adequate allowance is made for the altitudes at which the data were obtained. Writing the differential energy spectrum of the primary cosmic radiation as $j(E)$, and measuring E in Bev, the interinstrument comparisons are used to show that the average spectral changes approximate to the law: $\delta j(E)=\text{const}\times(1+E)^{-\beta}j(E)$, where $\beta\approx0.9$ for short-term variations, and $\beta\approx1.2$ for long-term variations.

It is shown that the amplitude of the long-term variation is markedly dependent upon altitude. Some evidence is presented that there might be a north-south asymmetry in the long-term variation, the amplitude being greater in southerly directions.

ELECTROMAGNETIC WAVES IN GRAVITATIONAL FIELDS. Jerzy Plebanski,* The Institute for Advanced Study, Princeton, New Jersey (Received September 21, 1959).

The scattering of plane electromagnetic waves by the gravitational field of an isolated physical system is studied. On the level of the geometrical optics approximation the general theory of light rays is formulated. In particular, the generalized formula for the Einstein deflection of light rays is obtained. On the level of the vectorial optics the problem of polarization is examined in detail. The formula obtained, describing a rotation of the plane of polarization due to the presence of the gravitational field, admits a direct geometrical interpretation. The theory is applied to the rotating body and a system of point masses. The physical results established concerning the asymptotic behavior of the electromagnetic waves are independent of the coordinate system used in the computations.

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QUANTUM LIMITATIONS ON THE MEASUREMENT OF GRAVITATIONAL FIELDS. Asher Peres and Nathan Rosen, Department of Physics, Israel Institute of Technology, Haifa, Israel (Received October 29, 1959).

By means of the analogy that exists between the gravitational field, in the weak, quasi-static case, and the electromagnetic field, uncertainty relations are obtained for the average values of some of the Christoffel symbols measured in two domains, similar to those for the components of the quantized electromagnetic field. Furthermore, it is shown that there exists a limitation on the accuracy to which the average value of a single one of these Christoffel symbols can be measured. The existence of uncertainty rela-

tions provides an argument in support of the standpoint that the gravitational field must be quantized.

APPLICATION OF DISPERSION RELATIONS TO K_{e3} AND $K_{\mu 3}$ DECAYS. R. F. Sawyer, Physics Department, University of Wisconsin, Madison, Wisconsin (Received October 26, 1959).

The decay modes, K_{e3} and $K_{\mu 3}$, are studied by means of a dispersion relation. It is assumed that the fundamental couplings involved are the strong pion and K-meson couplings to the baryons and a weak four-field coupling connecting nucleon, hyperon, and the lepton pair. The baryon-antibaryon pair contribution to the absorptive part of the decay amplitude is expressed in terms of the imaginary part of the pion propagator in the same approximation. The decay rate is determined in terms of the various coupling constants and the quantity Z which renormalizes the pion propagator. Comparison with experiment is made for the case $g_\pi^2/g_K^2 = 15$. The results are consistent with a hyperon leptonic decay coupling constant an order of magnitude less than the beta-decay strength.

PION-PION AND PION-KAON SCATTERING. Susumu Okubo,* Department of Physics and Astronomy, University of Rochester, Rochester, New York (Received September 28, 1959).

An easier derivation of the Chew-Mandelstam effective-range formula for pion-pion scattering is given using the conventional Feynman method with the interaction Hamiltonian $H_1 = 4\pi\lambda\phi^4$ in an approximation where only the chain diagrams are included. Furthermore, we have calculated a correction term to this formula due to the cross-diagram, both for S waves and for P waves. The same method has also been applied to pion-kaon scattering.

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PARTIAL-WAVE DISPERSION RELATIONS FOR THE PROCESS $\pi + \pi \rightarrow N + \bar{N}$. William R. Frazer and Jose R. Fulco, Lawrence Radiation Laboratory, University of California, Berkeley, California (Received October 9, 1959).

The problems of pion-nucleon and nucleon-nucleon scattering and nucleon electromagnetic structure involve the matrix element for two pions producing a nucleon-antinucleon pair. By use of the Mandelstam representation we are able to write dispersion relations for the partial-wave scattering amplitudes of this process. In the low-energy range these dispersion relations can be transformed into integral equations whose kernels are simply related to pion-nucleon and pion-pion scattering amplitudes.

EFFECT OF A PION-PION SCATTERING RESONANCE ON NUCLEON STRUCTURE. II. William R. Frazer and Jose R. Fulco,* Lawrence Radiation Laboratory, University of California, Berkeley, California (Received October 9, 1959).

It is shown that a resonance of suitable position and width in the $J=1$, $I=1$ state of the pion-pion system can bring the dispersion-theoretic calculation of the isotopic-vector part of the nucleon electromagnetic structure into agreement with experiment. The calculation of the isotopic-vector part of the nucleon form factors involves in first approximation the pion form factor and the matrix element for the production by two pions of a nucleon-antinucleon pair. For the pion form factor we used a semiphenomenological solution based on the work of Chew and Mandelstam and involving two parameters related to the position and width of the resonance. For the $\pi + \pi \rightarrow N + \bar{N}$ amplitude we used the results of the preceding paper.

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RELATIVISTIC PION-HYPERON DISPERSION RELATIONS. Richard H. Capps and Michael Nauenberg, Laboratory of Nuclear Studies, Cornell University, Ithaca, New York (Received October 26, 1959).

Relativistic fixed momentum-transfer dispersion relations are derived (but not proved) for pion scattering from Σ and Λ particles and the processes $\pi + \Lambda \rightleftharpoons \pi + \Sigma$. Separate equations for the S- and P-wave amplitudes are obtained under the assumptions that high-energy processes and baryon recoil may be neglected. The P-wave equations are identical to those derived from the Chew-Low theory for these processes. A brief discussion is given of the behavior of the P-wave amplitudes under the assumption of global sym-

metry. It is pointed out that the production of K-N pairs may play an important role in both the S- and P-wave equations.

ELECTRON-NEUTRINO AND ELECTRON-ANTINEUTRINO SCATTERING. R. W. King and D. C. Peaslee,* Purdue University, Lafayette, Indiana, and J. F. Perkins, Lockhead Aircraft Corporation, Marietta, Georgia (Received October 12, 1959).

Cross sections for electron-neutrino and electron-antineutrino scattering are given as a function of recoil electron energy. The electron-antineutrino cross section is averaged over a reactor spectrum of antineutrinos.

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EQUIVALENT HAMILTONIANS IN SCATTERING THEORY. H. Ekstein, Argonne National Laboratory, Lemont, Illinois (Received September 2, 1959).

This paper is a contribution to discussion of the question: To what extent does the scattering matrix determine the Hamiltonian? The Hamiltonians considered are nonrelativistic, but in extension of previous studies, "nonlocal" potentials and many-body potentials are allowed. A large class of unitary transformations is found which produce Hamiltonians leading to the same S matrix. In the last section, it is shown that this equivalence is only a special consequence of the general axiomatic formulation of scattering in field theory.

CANONICAL VARIABLES FOR GENERAL RELATIVITY. R. Arnowitt, Department of Physics, Syracuse University, Syracuse, New York, S. Deser, Department of Physics, Brandeis University, Waltham, Massachusetts, and C. W. Misner,* Universitetets Institut for Fysik, Copenhagen, Denmark (Received October 12, 1959).

The general theory of relativity is cast into normal Hamiltonian form in terms of two pairs of independent conjugate field variables. These variables are explicitly exhibited and obey ordinary Poisson bracket relations. This form is reached by imposing a simple set of coordinate conditions. It is shown that those functionals of the metric used as invariant coordinates do not appear explicitly in the Hamiltonian and momentum densities, so that the standard differential conservation laws hold. The bearing of these results on the quantization problem is discussed.

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ANNOUNCEMENT

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